The Dissertation Committee for Raed Tahsin Jarrah certifies that this is the approved version of the following dissertation:

Planning for, Facilitating, and Evaluating Design Effectiveness

Committee:

James T. O'Connor, Supervisor

William O'Brien

Carlos Caldas

David Fowler

William Kelly

Planning for, Facilitating, and Evaluating Design Effectiveness

by

Raed Tahsin Jarrah, B.E.; M.S.

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To my wonderful parents, Tahsin Fawzi Jarrah and Hiba M. Hasan Saadi.

Planning for, Facilitating, and Evaluating Design Effectiveness

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Raed Tahsin Jarrah, Ph.D

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Supervisor: James T. O'Connor

Design Effectiveness is the degree to which the design effort helps in achieving project value objectives. Because Design Effectiveness largely exists within the context of the design phase, considerations on other project phases, such as front-end development or construction management, have been excluded from this study. Practices that promote Design Effectiveness are called Design Effectiveness Practices (DEPs), and the primary aim of this research was to develop a method for identifying suitable DEPs on a given project.

The research consisted of three segments. The first segment of the research consisted of an ANOVA analysis of the CII benchmarking database to analyze the effect of Design on project performance metrics. The second (and main) segment of the research was the development and validation of a Design Effectiveness Practices Selection Tool. The MS Excel® based tool determines the priority of application of 30 different DEPs on a project given the project's desired benefits (from 11 Project Value Objectives), design phase, and unique characteristics. All the 30 DEPs were correlated with the three input parameters using Score Matrices with the aid of expert opinion. The Score Matrices produced a score for each of the input parameters, and the three scores were combined to form a Composite Index Score for each DEP. The Selection tool was also validated in a two-step process, and met the validation thresholds set out for it. The third segment of this research involved the development of a Design Effectiveness Evaluation Tool, also based on MS Excel®.

This dissertation contributes to a growing area of research by providing comprehensive, structured compilation of DEPs and also by developing a selection method to effectively recommend the most suitable DEPs. From the perspective of the industry, the results of this research (and most notably the Selection Tool), facilitate the implementation of the DEPs and should help in maximizing the potential benefits to a particular project.

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Chapter 1: Introduction

1.1 *Context and Need:*

Owners, architects, engineers and contractors in both the private and public environments devote all their efforts to delivering and operating successful projects. Industry professionals are committed to the goal of having projects turn out well. Unfortunately, the industry's track record is not perfect. In fact, recent history is littered with many examples of projects that have not succeeded as well as desired. In many instances, critical aspects of design were either poorly executed or overlooked altogether. In some projects, the consequences were severe. Many such failures resulted in excessive costs to correct deficiencies, unexpectedly high operating expense, or even loss of life.

The Construction Industry Institute (CII) formed a Design Task Force in the spring of 1984. That group produced CII Publication 8-1, "Evaluation of Design Effectiveness," in July of 1986. The Introduction to Publication 8-1 states, "…design is perhaps the most central point of definition for a project in that ideas and information are transcribed to paper in the form of specific and coordinated instructions for the project's construction and documentation." Although design processes and methods have evolved over the last 20 years, the idea expressed by that statement still applies.

The research conducted in association with Publication 8-1 was relatively narrow in scope and, not surprisingly, did not reflect many subsequent developments that can enhance design effectiveness. For example, methods and processes such as Pre-project Planning, Planning for Start Up, Value Management Processes, Risk-Based Design, 3D and 4D CADD, BIM Technologies, and Design for Constructability, Operability, and Sustainability are now commonly applied within the industry.

As a part of this research, RT 233 updated the definition of Design Effectiveness as: "the degree to which the design effort achieves project value objectives".

1.2 *Purpose and Objectives:*

RT-233 was formed in the fall of 2005 in recognition that Publication 8-1 had become outdated. From the beginning, RT-233 sought not only to update the evaluation methodology and criteria, but also to emphasize the importance of proactive planning for Design Effectiveness and to identify and characterize supportive tools and processes. In today's environment, project objectives fall into many different categories, and a completed project that performs well with regard to some objectives while missing the mark on others is seldom considered a success. Thus, direction and guidance are needed to address the breadth of project objectives and to better exploit underutilized or recently emerged Design Effectiveness practices. In conducting its research, the team sought to identify and characterize Design Effectiveness practices and processes by which designers and their design products can be more responsive to procurement, construction, startup, operations, and maintenance needs.

1.3 *Scope Limitations:*

The scope of the quantitative study was to explore the effect of design on project performance metrics. This study collected data from the CII Benchmarking Database, which contained 1498 data entries from projects between 1990 and 2003. Owner and contractor data were analyzed separately, using six dependent variables and seven independent variables. Due to the data quality and the nominal nature of some variables, regression analysis or data-mining techniques were not possible beyond a simple ANOVA. This exploratory study was undertaken to add value to the purpose behind the main Design Effectiveness research conducted in the rest of the research project.

The scope of this research and the tools produced was limited to consideration and application of those practices that impact design effectiveness. This research effort was not directed at broader business practices and other non-design related project activities that also contributed to a project's success. Moreover, the expert panel on RT233 was compromised mostly of individuals involved in the industrial sector of the construction industry (Owners, Designers, and Contractors), and to a lesser extent, the commercial building sector. As such, engineering / residential sector Design Effectiveness concerns were explicitly addressed by the panel (see Appendix K for details).

Figure 1.1 provides another view of the context of Design Effectiveness, which relies on both successful project management and successful design management.

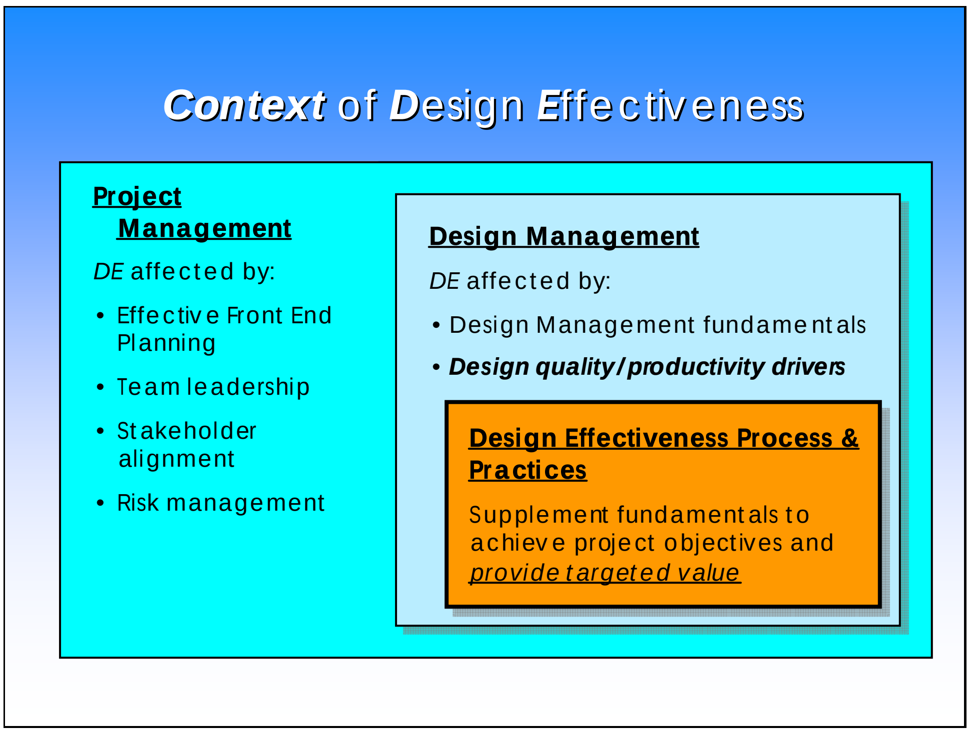


Figure 1.1: Context of Design Effectiveness

In addition, as many related publications are available, this research does not address how to perform specific design effectiveness practices at the detailed, tactical level. The emphasis here is on strategic practice selection, timely implementation, and objective-driven evaluation of design effectiveness.

1.4 *Structure of Dissertation:*

This document is arranged into eight chapters. It begins with an Introduction chapter, which contains the research context, objectives, and scope limitations. Chapter 2 is a literature review on the topics of Design Effectiveness, evaluation, and ANOVA. Chapter 3 covers the methodology of the research, which is organized into three major phases: the ANOVA analysis, the DEP Selection Tool, and the Design Effectiveness Evaluation Tool. Chapter 4 delves into the details and results of the ANOVA analysis. Chapter 5 covers the development of the DEP Selection Tool and provides screenshots of the application tool. In continuation, Chapter 6 covers the details and results of the validation process on the DEP selection tool. Chapter 7 then covers the details of the development of the Design Effectiveness Evaluation Tool, along with screenshots. Finally, Chapter 8 provides the conclusions and recommendations of the research.

Chapter 2: Literature Review

This literature review covers the topics related to Design Effectiveness and the processes of selection and evaluation. Design Effectiveness involves a wide array of topics with the basic element being design itself. After covering the basics of Design Effectiveness, this chapter discusses the input and output variables involved in early Design Effectiveness research. An overview of methods of evaluation is presented, along with a section on the original "engine" used for Design Effectiveness Evaluation, the Objectives Matrix. This review also covers the selection process for Value Management Process, with focus on the algorithm and validation. In addition, this chapter covers the basics of ANOVA, which was used to analyze the relationship between design and project performance metrics in this research.

2.1 *Design Effectiveness*

Design may be defined as an iterative process utilizing the available technical and managerial resources to produce plans and specifications to satisfy the owner's needs on a project, while dealing with physical, financial, and environmental constrains. Most owners, designers, and contractors interpret design as a home office effort that encompasses:

- Preliminary Design
- Project Management and Controls
- Procurement
- Detailed Design

The major parties on the project (owner, designer, contractor, and sometimes even the sub-contractor and vendors) are involved in the design tasks mentioned above, with varying degrees of emphasis and responsibility. By extension, Design Effectiveness could be defined as “a measure of the design efforts against the expectations of the owner” (Broaddus, 1991).

Design effectiveness might seem a simple term, but is a field that can cover many areas and definitions. Design Effectiveness could be as simple as setting proper scope to reduce overall project cost (Chalabi et al., 1987), or implementing standards and systems to enhance communication and performance between the Owner and the Architect (Anderson and Tucker, 1994). Design Effectiveness Practices are implemented during the course of the project design phase with the aim of enhancing the effectiveness of design. This could cover several areas, from cost/time/quality of the design itself, to the construction process, and even beyond to the operation and maintenance of the facility.

Other parties might be involved in the design process beyond the owner and designer. This could include vendors, consultants, and even contractors. As such, it becomes difficult to identify and evaluate the design effectiveness of one particular player in the project; it is much more practical to evaluate the overall result from all the contributors (Tucker, 1986).

Quantitatively comparing unique projects in the construction industry, especially "creative" components such as design, has been a challenge for managers (Broaddus, 1991). The need for benchmarks, however, is paramount for tracking performance and identifying areas in need of improvement. After all, problem-finding is the first step in problem-solving.

There are two dilemmas that arise in evaluating design effectiveness across different projects, both branching from the concept that construction projects are "unique". The first is identifying the common grounds (while factoring in the unique constraints) between past projects and new projects to utilize the applicable "lessons learned" from previous situations. The second dilemma is related to very unique or "pioneer" projects. It is the inability to confidently assess the overall outcome of a project plan until is it is substantially completed due to the lack of comparable projects and the number of variables involved in the project. As such, the only way to know how the project design will perform is to carry out that design. This puts the management team in a disadvantageous position where they have to monitor the project as it develops and react to problems accordingly (usually in an "after-the-fact" manner) , as opposed to tackling issues proactively if they had a knowledge base of possible problems and obstacles.

2.2 *Design Effectiveness Input and Output Variables*

Input variables to Design Effectiveness feature practices and decisions made in order to enhance the project's effectiveness of design. These include the level of communication, scope definition, pre-project planning, etc (Chalabi et al., 1987). Evaluating Design Effectiveness, however, needs to consider output variables as well. Keep in mind that Design Productivity parameters are not synonymous with Design Effectiveness outputs. Man-hours and design time are considered Design Productivity parameters, but design quality and total cost are Design Effectiveness outputs.

A study on the relationship between Design Effectiveness inputs and project success (Broaddus, 1991) identified Scope Definition, Objectives & Priorities, Acquisition Planning, Designer Qualifications, and the A/E Contract Process as some of its inputs. The outputs in the study were Cost Variability, Schedule Performance, Design Quality, and Constructability. Both sets were run through objective matrices in the process of analysis with the aim of comparison and benchmarking.

The output variables in the Broaddus study were derived from previous research by Tucker. The previous study had 7 output variables: Accuracy of Documents, Usability of Design Documents, Cost of Design, Constructability, Economy of Design, Performance against Schedule, and Ease of Start-up. The Tucker study identified these output variables as objective and/or subjective. The Broaddus study attempted to give more focus and weight to objective variables.

2.3 *Timing Impact of Implementation of Best Practices*

A general representation of the phases of a construction project is as follows (Tucker 1986):

1. Conceptual / preliminary analysis
2. Project initiation, designer selection, project organization
3. Basic engineering
4. Detail planning
5. Production engineering and procurement
6. Construction
7. Commission

Project design is generally from the "project initiation" to the "procurement" phases, but the influence of Design Effectiveness decisions is most profound at the very start of the project. As project develops, more elements and decisions get locked in and it becomes increasingly difficult to change or implement new ideas.

The timing of implementation is quite influential; the owner plays a very important role in a project's design effectiveness even before a designer has been selected (Broaddus, 1991). The owner's decisions in the very early stages of design set the foundation upon which the later players (the designer and contractor) will be working on, and determine the level of flexibility in the application of other design effectiveness practice as the project develops. Tucker's research illustrates the decline of decision influence as a project develops (Figure 2.1).

Implementation of practices earlier in the project's design phase has a greater impact on the project overall (Broaddus, 1991). Decisions made in the later period of the project would be more constrained with time, and some practices are inapplicable beyond a certain stage of the project. The quality of implementation of Design Effectiveness Practices also plays a defining role in the level of improvement that can be achieved on a project.

Although previous research mentioned the importance of timing in design effectiveness, the project phase of implementation itself was not singled out as an input variable. Instead, it was assumed that processes of implantation of design effectiveness practices and decisions were taking place early in the project life. Therefore the affects of late-implementation were not included in the studies.

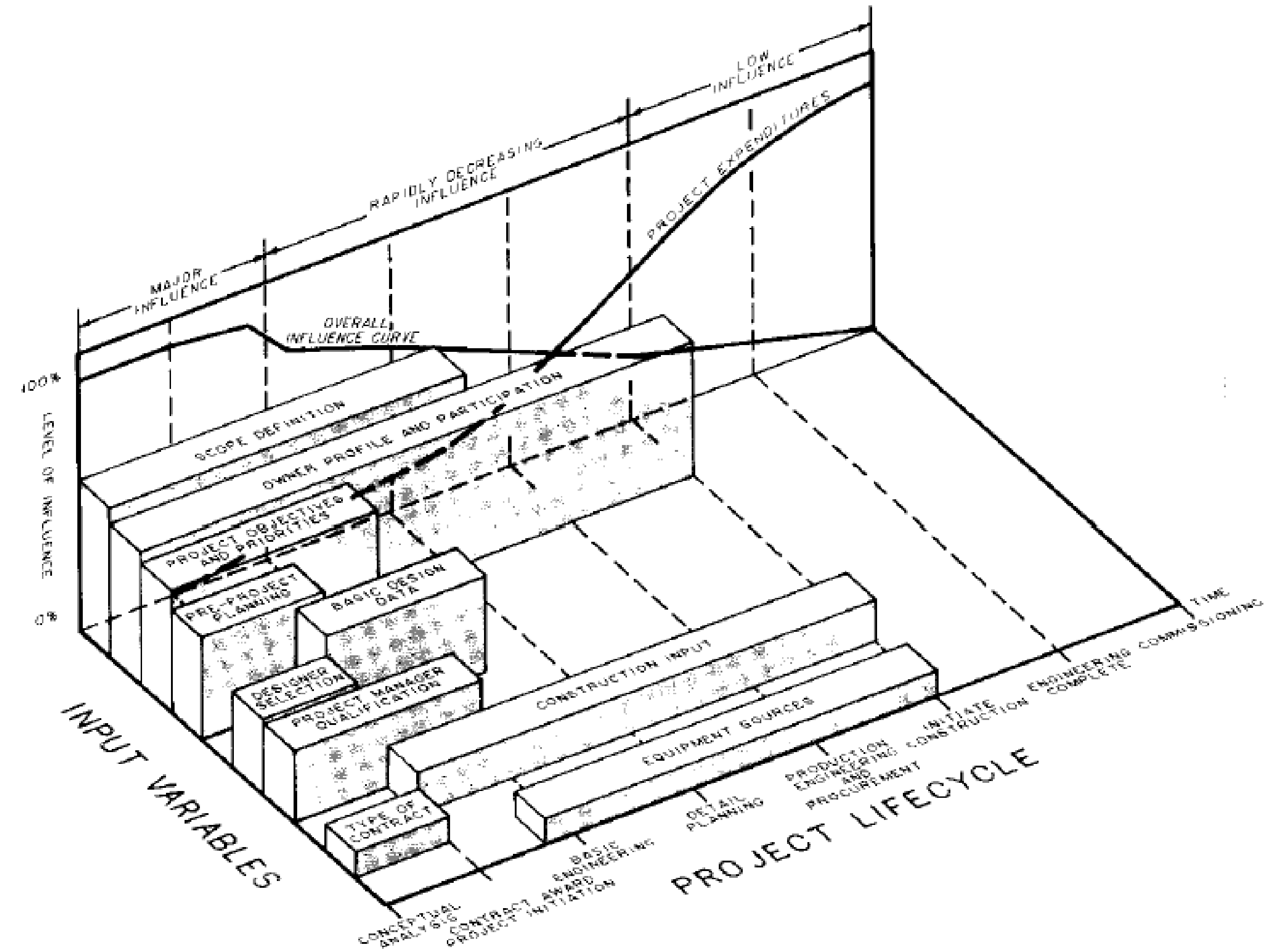


Figure 2.1: Design Influence Diagram (Tucker, 1986)

2.4 *Methods of Evaluation*

Evaluation can be approached objectively or subjectively, and it can be from an Elite or Mass perspective (House, 1978). The Elite perspective tends to approach the issue from the eyes of experts, while the Mass perspective is from a much wider base. There are also different levels of "orientation": political (pseudo-evaluation), questions (quasi-evaluation), or values (true-evaluation) (Stufflebeam and Webster, 1980). The political orientation provides a positive or negative view of an object regardless of what its true value might actually be. The questions orientation consists of approaches that might or might not provide answers specifically related to an object's value. The values orientation includes methods made to directly determine the object's value. Table 2.1 provides some evaluation approaches (House, 1978 and Stufflebeam and Webster, 1980).

Politically controlled and public relations studies are objectivist, elite, pseudo-evaluations. They attempt to misrepresent value interpretations, each in its own way. Information obtained through politically controlled studies can be released or withheld according to the special interests of the evaluator. Information in Public relations can used to bolster the image of an object regardless of its actual value. Neither of these approaches is an acceptable evaluation practice.

Table 2.1: Classification of Evaluation Approaches (House, 1978 and Stufflebeam & Webster, 1980).

		Political (Pseudo-evaluation)	**Questions (Quasi-evaluation)**	**Values (True evaluation)**
Objective	**Elite (Managerial)**	▪ Politically controlled ▪ Public relations	▪ Experimental research ▪ Management information systems ▪ Testing programs ▪ Objectives-based ▪ Content analysis	▪ Decision-oriented ▪ Policy studies
	Mass (Consumers)		▪ Accountablity	▪ Consumer-oriented
Subjective	**Elite (Professional)**			▪ Certification ▪ Connoisseur
	Mass (Participatory)			▪ Adversary ▪ Client-centered

Table 2.1 lists five popular and respected approaches under objectivist, elite, and quasi-evaluation. They are considered quasi-evaluation approaches because particular studies can focus only on questions of knowledge without addressing any questions of value. Experimental research is the best approach for determining causal relationships between variables. However, it is a highly-controlled method and may be too slow to dynamically changing situations. On the other hand, Management information systems (MISs) can give detailed information about the dynamic operations of complex programs, but this information is restricted to readily quantifiable data (and usually available at regular intervals). Testing programs are good at comparing individuals or groups to selected norms in a set of standards of performance, but only focus on the subject's performance.

Objectives-based approaches relate outcomes to a set of objectives, allowing judgments to be made about their level of attainment. The objectives must be relative to the subject and must not focus on outcomes that are too narrow. Content analysis is considered a quasi-evaluation approach because content analysis judgments need not be based on value statements, and can instead be based on knowledge. However for a content analysis to be considered an evaluation its judgments must be based on values.

Of the Objectivist, mass, quasi-evaluation approaches, Accountability is quite popular because it is intended to provide an accurate accounting of results that can improve the quality of products and services. Caution must be used to avoid turning this method into a form of biased advertisement.

Decision-oriented studies (objectivist, elite, true evaluation) are designed to provide a knowledge base for making and defending decisions. This approach usually requires collaboration between an evaluator and decision-maker, allowing it to be open to bias.

Accreditation / certification programs are a form of subjectivist, elite, true evaluation. They are based on self-study and peer reviews. They draw on the insights, experience, and expertise of qualified individuals who use established guidelines to determine approval. Connoisseur studies use the highly refined skills of experts in the subject of the evaluation to critically characterize and appraise it. The drawback is finding a qualified and unbiased expert.

Among subjectivist, mass, true evaluations, the adversary approach focuses on drawing out the advantages and disadvantages of issues through “quasi-legal” proceedings. This helps ensure a balanced presentation of different perspectives on the issues, but can also discourage later cooperation and heighten animosities between contesting parties. Client-centered studies address specific concerns and issues of practitioners and other clients of the study in a particular setting. These studies help people understand the activities and values involved from a variety of perspectives. However, this responsive approach can lead to low external credibility and a favorable bias toward those who participated in the study.

This study relies on the Objectives Matrix to approach the evaluation of design from an objectivist, elite, quasi-evaluation perspective. It borrows some elements of the expert (or connoisseur) approach in order to determine the criteria weights, but it still remains a mainly objective approach.

2.5 *The Objectives Matrix*

The Objective Matrix allows for the relative assessment of a project objective based on the weighting and scoring of elements or “indicators” of objective (Peek, 1987). The Objective Matrix was first introduced by Riggs in 1985. The Objectives Matrix consists of four elements: the criteria, weights, performance scale, and performance index. The criteria define the object being measured, the weights tell the relative importance of the criteria to one another, and the performance scale compares a criterion's value to a selected benchmark. The three components are used to calculate the performance index, which is used as an index to track performance (Riggs, 1985).

The Tucker study used 7 attributes in the output objectives matrix (see Figure 2.2). Each of attributes contained two to six sub-criteria, which were used in objective matrices for each attribute to derive the attributes score. The 7 attribute scores were then used a more general objectives matrix to derive the index score for design effectiveness. The performance scale used was a 0-10 scale, with 3 as an average. The weights for each criterion (or element) were multiplied with the score to produce the criterion's "value". The sum of the "values" produced the performance index for that objectives matrix.

When selecting the criteria for an objectives matrix, they must be: Specific, Measurable, Acceptable, Realistic, and Time-terminated. Criteria must be specific and well-defined to avoid misinterpretation. They must be measurable to gauge them against a benchmark (even qualitative criteria can measurable if the benchmarks are set properly). The criteria must also be acceptable (or achievable) and realistic, as measuring unattainable or unreliable criteria would skew the objective's matrix results. Finally, the criteria values must be bound by time, as an infinitely changing criterion cannot be used for benchmarking. One more factor that is important in the development of the objectives matrix is independence among criteria. Interdependence would violate the concept behind creating an index score from independent components.

Determining the criteria weights is an exercise by itself. Many methods can be used to determine the weight values. Pervious research on the criteria's topic might help in this task. One approach would be the use of Analytical Hierarchy Process, where the criteria are listed on a matrix's top rows and columns, and a relative "multiplier" is used to indicate the relative importance of one criterion over another. The next step would be to eliminate inconsistencies and normalize the weights. Since AHP is a tedious process, other, simpler methods of weight determination can be applied. These involve using a simple scale (low, medium, high) and do not involve several iterations. Some methods rely on a small group of experts to assemble the relative weights, with some methods asking the experts to reach a consensus, and others simply averaging their responses. Some methods replace the expert panel with a large survey sample size and average the responses. The method selected should consider the number of criteria being weighted and the level of expertise required. AHP becomes increasingly difficult to implement when weighting more than 10 criteria (Clemen and Reilly, 1996), while some criteria cannot be weighted using a large sample survey due to the level of expertise required to understand them.

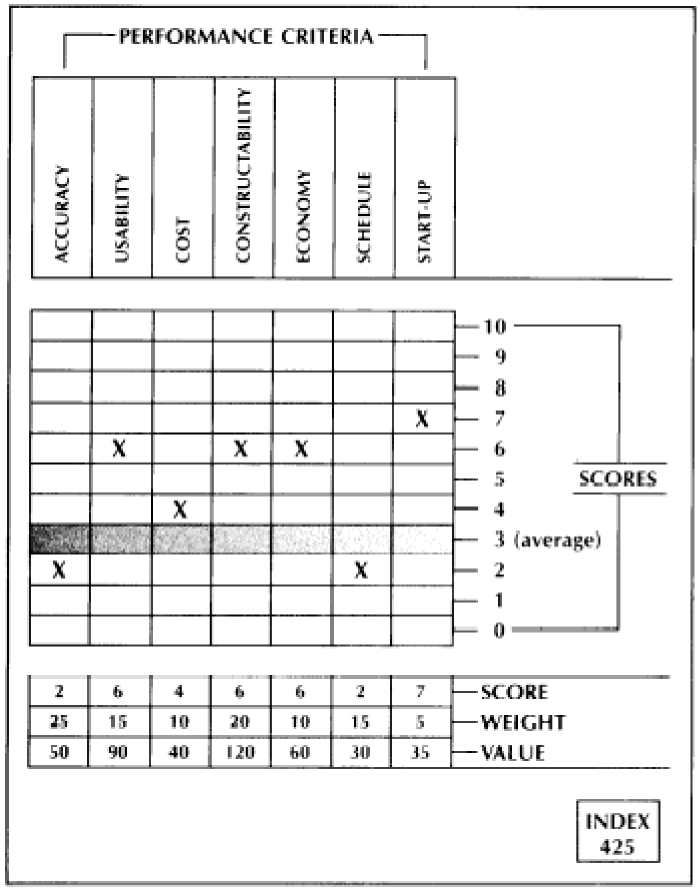


Figure 2.2: Example of an Output Objectives Matrix (Tucker, 1986)

The performance score for a criterion can be determined through judgment, a quantitative score, or a combination of sub-criteria in sub-matrices. The judgmental approach can be applied to some or all the criteria, despite its drawback of subjectivity, since the use of multiple criteria and different weights would still make it a valid application (Tucker, 1986). The quantitative score utilizes a set of quantitative values to benchmark against the criterion's value. For example, a safety criterion could utilize the number of annual injuries on site per 1000 workers per year and compare that to a benchmark of values with an upper limit, a lower limit, and an average. The sub-criterion or sub-matrix method relies on using the same process of the objectives matrix to determine the score of criterion: by using a set of weighted sub-criteria to produce a sub-index. This sub-index would be used as the criterion's score.

In the case of quantitative criteria, it becomes harder to set up a performance scale. One way to approach the problem is to construct a scale for measuring the criterion on general terms (Clemen and Reilly, 1996). By defining a number of meaningful levels (Worst, Low, Medium, High, Best), one can have a basis on which to score the qualitative criterion. The descriptions of each level can be a set of qualifications or examples. The qualifications approach is similar to the sub-matrix method in quantitative criteria, while the example approach is closer to the benchmark method.

Finally, the performance index is the result of multiplying the criteria weights by their scores, and summing the results. The performance index will have a maximum value of the sum-product of the criterion's maximum scores by the weights. In Figure 2.2, the performance scale is 0-10, with 3 as an average, while the weights sum to 100. As such, the maximum performance index value is 1,000, while the average is 300. These boundaries can be used to track and benchmark the performance index.

2.6 *Additive Utility Function*

2.6.1 Basics of the Additive Utility Function in Decision Making

Fishburn (1970) provided guidelines for using utility functions as a tool in decision making. Focusing on human preference in the decision making process, Fishburn approached the process from two perspectives: decisions made under certainty (or suppression of uncertainty), and decisions made under uncertainty.

The concept of making decisions is based on preference of utility; the option that provides greater utility would be more preferable. In the case of decisions made under certainty, the set of decision alternatives were examined as finite and infinite. Fishburn presented cases of multi-factor decision problems, examples of "persistent preference difference", and touched on the concept of preference intensity. He also provided conditions that would suggest that the utility of a whole could be expressed as the sum of the utilities of the parts.

In the case of decisions under uncertainty, Fishburn provided models of probability distributions to apply to the utility functions. He provided cases that assumed indifference between alternatives was transient, and cases that did not use that assumption. Uncertainty was then combined with multi-factor consequences, and conditions for assuming the utility of a whole was the sum of the utilities of the parts.

2.6.2 Additive Utility Functions and Objectives Matrices

The additive utility function is the mathematical approach of applying the objectives matrix (Clemen and Reilly, 1996). The main concepts that apply to developing an objectives matrix also apply here. The set of objectives must be complete, yet as small as possible, and should not contain redundancies. The criteria should be reduced to their simplest form when possible (e.g.: if a criterion is based on cost and schedule, it should be made into two criteria). Also, the criteria should have a performance scale that is defined, functional, and as straightforward as possible.

The Additive Utility Function produces an index score through the sum-product of the criterion scores and weights. The weights are designed by default to add up to 1, and the score-scale is from 0 to 1. Therefore, the maximum value of the index is 1, and its minimum value is 0. The score scale of a criterion transforms the best value of that criterion to a 1, and the worst value as a 0. Setting the best and worst value can be done either by establishing a benchmark or using the available data in a sample. The latter approach tends to be more limiting for the index, but the former option is not always available.

Weights can be assigned through several approaches. One would be to assign a bid value for one of the criterion over another. In other words, this method asks "how many units of the first criterion are you willing to sacrifice to gain one unit in the second criteria?" Considering that the weights sum up to 1, one only needs to make N-1 different criteria comparisons (where N = number of criteria) to be able to solve the equations and derive the weight values. Another approach is similar to the AHP method, and relies on establishing multipliers and ratios between criteria to determine the weight values.

Another weighting method is "swing weighting". This method relies on producing weights for criteria by hypothesizing about the best and worst situations. The approach starts off by establishing an overall worst case scenario (worst values for all criterion), then produces N more scenarios, each based off the worst case scenario but replacing one criterion with its best value. The scenarios are then ranked, starting with the worst case scenario receiving the lowest rank by default. The rankings are then given ratings, with the lowest rank getting a rating of 0 and the highest rank getting a rating of 100. The ranks in between can be assigned ratings through direct interpolation or according to custom relative ratios (for better customization).

One more method would be the use of indifference probabilities. This method is essentially similar to the bidding method described before, but relies on establishing an indifference probability. The question asked here is: "If one option was having the best of one attribute but the worst on the rest, and the other option was a lottery between the best on all attributes and the worst on all attributes, what is the probability of getting the very best attribute scenario in the lottery that would make me indifferent in picking between the lottery decision or the one best attribute but the rest are worst decision?". This indifference probability is then used to produce an equation that can be used to solve for the weight values. While the bidding method asks how much one is willing to sacrifice, the lottery method asks how much risk one is willing to put in uncertainty.

2.7 *Value Management Processes (VMP) Selection Process*

Previous research efforts have been made to identify a selection algorithm for 44 Value Management Processes (VMPs) by HeeSung Cha (2003). The study incorporated Timing, Project Value Objectives, and Suitability Factors as inputs. These input variables were run through objectives matrices, and the resulting index was used to rank the VMPs according to suitability for a given project (see Figure 2.3).

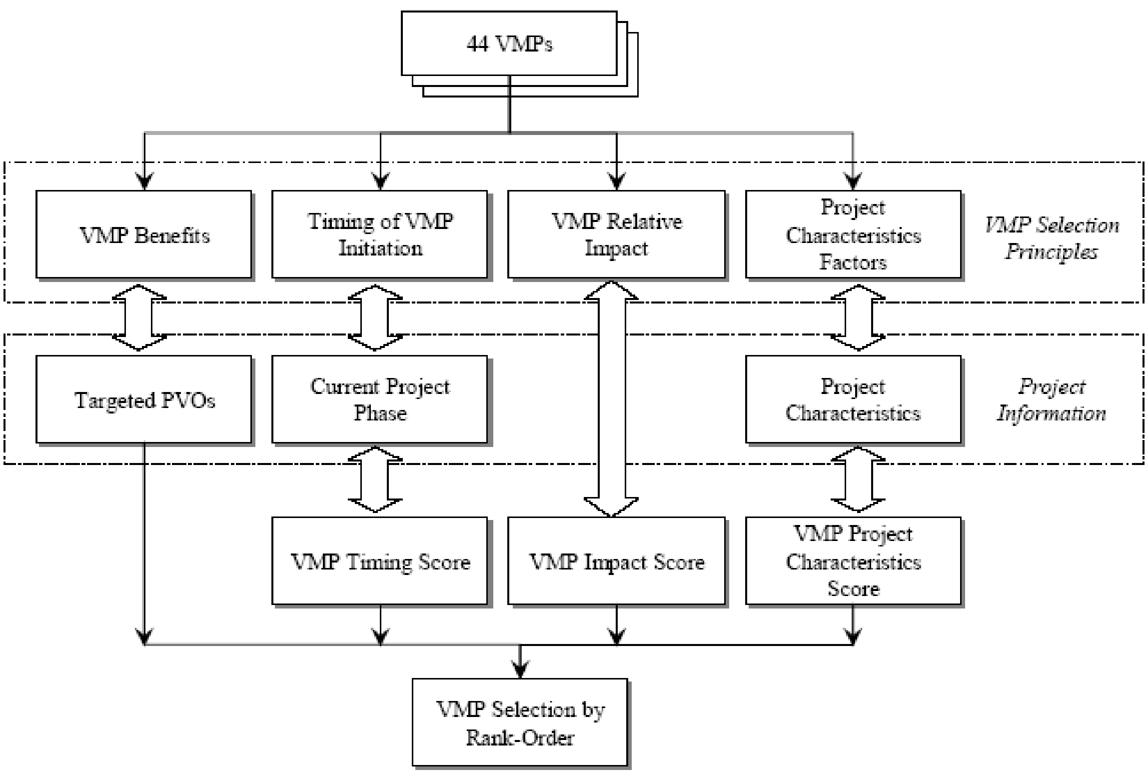


Figure 2.3: VMP Selection Process

The Timing input variable factored the project phase at which the VMPs were going to be implemented. Based on the concept that it becomes increasingly difficult to influence performance as a project gets into its later stages, the Timing objectives matrix contained higher values for VMPs implemented during the Planning and Early Design phases, and lower values for the Construction and Operations & Maintenance phases.

The second input variable, Project Value Objectives, gauged the desired benefits sought for the project (Safety, Regulatory Compliance, Capital Cost Efficiency, etc.). The desired benefits' objective matrix matched each of the 44 VMPs to the 12 Project Value Objectives with a high, medium, or no influence. As such, VMPs that strongly matched the selected PVO criteria resulted with a higher index value than those that did not.

The third input variable was Suitability Factors. A list of 149 suitability factors was complied, and each VMP corresponded to 8-10 of those factors non-exclusively. The study developed the weighting of each Suitability factor by weighting each one in relation to the other factors within a VMP set. These weights were used to create the objectives matrix for the Suitability Factors. A VMP would receive a higher index score as it captured more suitability factors.

The final output of the process multiplied the Timing objectives matrix output by the average of the PVO and Suitability Factors outputs. The resulting index was used to rank the suitability of the VMPs for a project. The higher the final index of a VMP, the more suitable it was for the project. The rank helped sort the VMPs in order of importance, but the score itself indicated the recommended applicability of he VMPS. A low-scoring VMP that with a high rank was not as recommended as a high scoring VMP with a medium rank.

The selection algorithm was implemented into an Excel® spreadsheet program (see Figure 2.4). The selection tool guided the user through a series of pages and that derived the input values, discretely processed them through the objectives matrices, and displayed the results. The tool featured an intelligent filtering system that filtered out the unnecessary input questions based on the user selection of the VMP selection pool and the desired benefits.

The selection tool was validated with a two-step survey, which was handed out to a variety of 5 members in the construction industry. The first step was manual survey that asked the participants to list the suitable VMPs for their project based first on intuition, and then on a guided, structured assessment similar to the research's algorithm. The second step involved using the Excel® selection tool to again assess the VMP rankings for the project. The results of the Manual and Selection Tool Processes were then compared for match rate and consistency of rank.

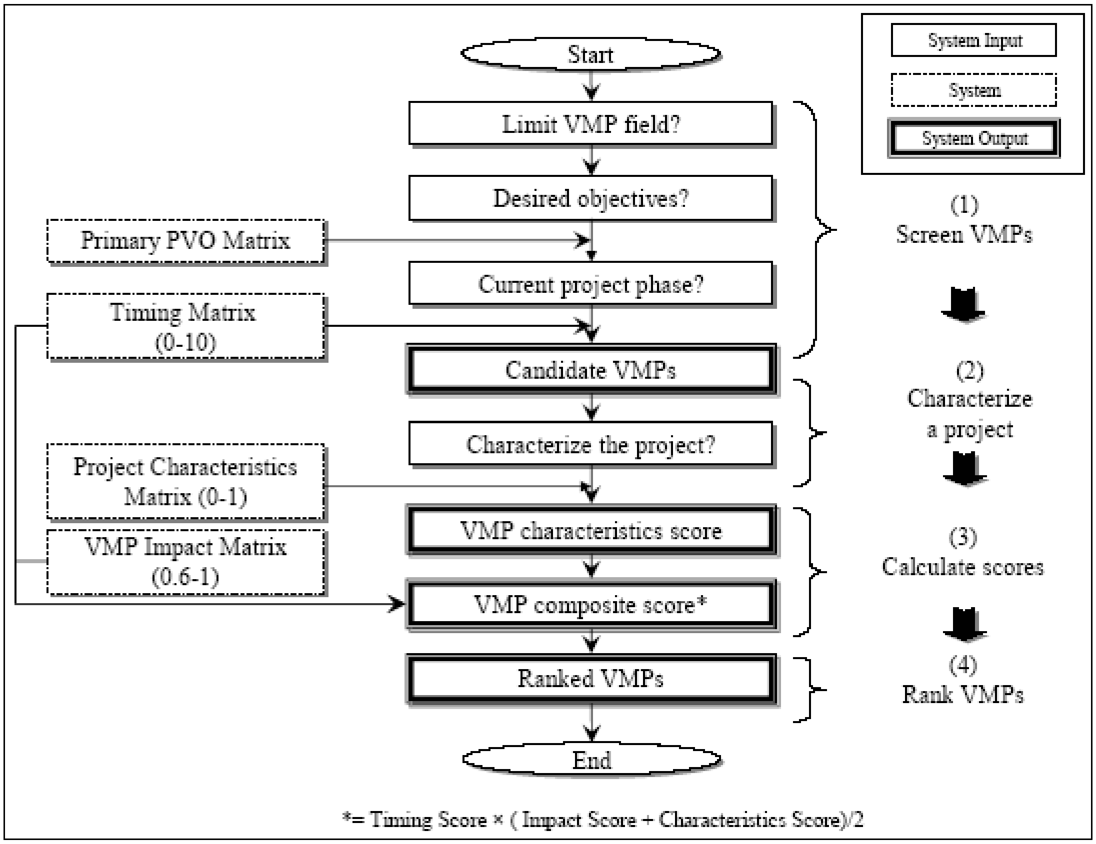


Figure 2.4: VMP Selection Tool Logic

The validation proceeded with an added step of conducting a phone interview to ask survey participants about the selection tool's performance. The responses were mostly positive, but some of the comments could be considered as a "lessons learned" for the study. One of the comments mentioned that the project team should be familiar with the project characteristics to produce reliable results. Another comment was that detailed follow-up implementation guidance is needed, since the project team may be concerned with what to do after the completion of the VMP selection process (the Value Management Toolkit can be used as a key resource).

2.8 *ANOVA*

The basics of statistical analysis is hypothesis testing. In the world of statistics the general motivation behind tests is to prove a significance of difference between values. However, since it is mathematically impossible to test for each and every possible value in a distribution, statisticians rely on disproving the opposite scenario, or Null hypothesis. If one were aiming to prove a significant difference between two means, then the null hypothesis would be that the two means are significantly equal. If statistical tests show that the two means were not significantly equal, then the null hypothesis would have been disproved, and thus the alternate hypothesis proved.

The degree of significance is determined by a confidence level (generally denoted as α). An α of 0.05 indicates a confidence level of 95%, and an α of 0.01 a level of 99%. To disprove a null hypothesis stating that two means are equal within a confidence level, the difference between the means has to be greater than the confidence level. For example, the value of one of the means is large enough that it only has a 3% chance of occurrence given the distribution of the other mean. As such, one can state that the null hypothesis is false (and thus the alternate hypothesis is true) for a confidence of 95%.

The most basic statistical test, the Z-test, finds the cumulative probability of a given value on a normal curve with a mean value of 0 and a standard deviation of 1. Through the concept of transformations, the probability of occurrence of a given value can be derived for any given normal distribution. The Z-value is derived as follows:

$$Z = \frac{x - \mu}{\sigma}$$

Where:

x = Value whose cumulative probability is being sought

μ = Mean of the distribution (of which x is being measured on)

σ = Standard Deviation of the distribution (of which x is being measured on)

The null hypothesis can be proven as false if the cumulative probability of x (on the given distribution) exceeds the confidence level limits (1-α in a one-tail test) set in the test.

The Z-test does not provide an accurate test for small sample sizes. As such, a T-test is used to provide a more accurate result. The T-test is basically a Z-test with a variable normal distribution based on the sample size given. Smaller sample-size values would have more conservative values for a given confidence interval as compared to larger sample sizes. T-Test values of sample sizes of 30 or more would be almost identical to those of a Z-test. The T-test is based on the concept of "degrees of freedom" within a group; the larger the degrees of freedom, the less stringent the conditions for proof of significance. Degrees of freedom (within a group) are calculates as the sample size minus one (N-1).

The Analysis of Variance (ANOVA) is a method of comparing the mean values of groups versus the variation between and within the groups (Damon, 1987). It is based on a method of comparison similar to the T-test, but unlike the T-test it is capable of comparing more than 2 groups simultaneously. ANOVA uses a statistic called F, which is essentially equal to t^2 is the case of comparing two groups for significance. The F-statistic depends on two forms of degrees of freedom: the degrees of freedom between groups (calculates as the number of groups minus 1, or K-1), and the degrees of freedom within groups (calculated as the sample size minus the number of groups, or N-K). The value of the F-statistic required for significance increases with higher between-groups degrees of freedom (more groups), and decreases with higher within-groups degrees of freedom (higher sample sizes for the same number of groups). Of course, this is all relative to the same significance level selected.

ANOVA analyzes the variance between and within groups. As such, groups with small variance within the group but with large variance between the groups tend to have their means significantly different (Figure 2.5). Groups with large variance within the group but with small variance between groups tend to have means that are not significantly different (Figure 2.6). In the former case, there is a low probability that the means of one group would lie within the distribution of another group, while in the latter case the probability might be too high to indicate significant difference.

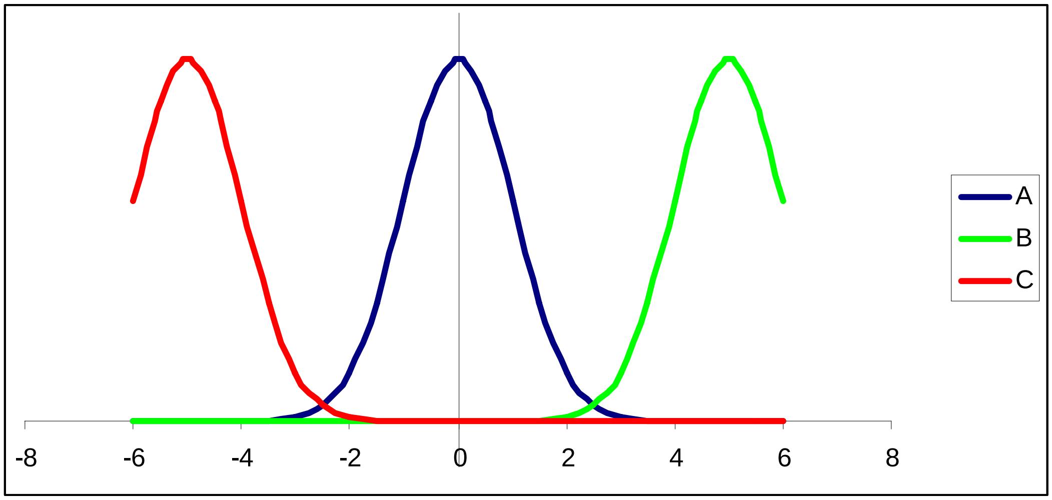


Figure 2.5: Small variance within groups and large variance between groups

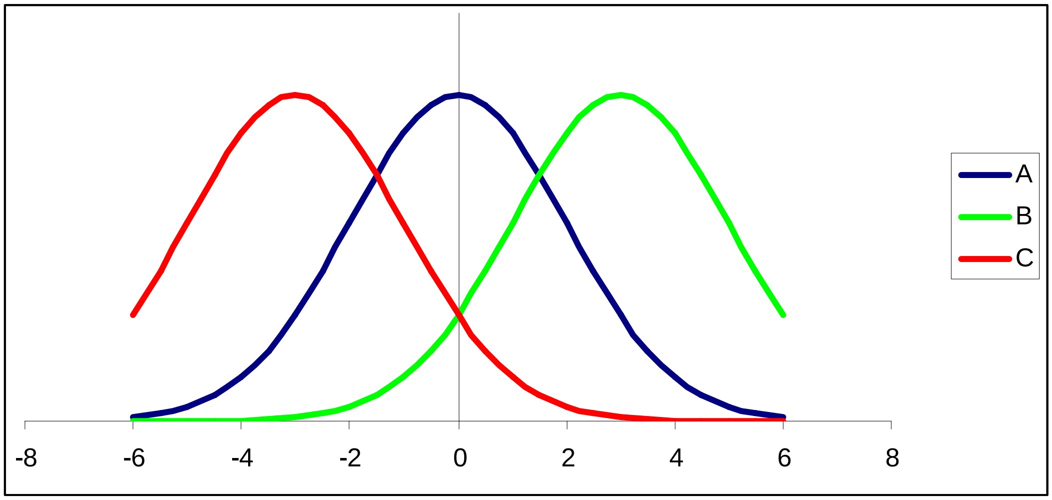


Figure 2.6: Large variance within groups and small variance between groups

Chapter 3: Methodology

3.1 *Methodology Overview:*

The research began with a quantitative analysis of the effect of design on project performance metrics. Data was collected from the CII benchmarking database, with owner and contractor data analyzed separately. Seven independent and six dependent variables were derived from the database. The data was filtered for outliers and duplicates, as well as entries with missing data. Finally, the data was analyzed using ANOVA. Due to the nominal nature of some of the independent variables, the data was further analyzed in quartiles and halves (ex: analyzing the top quartile entries versus the bottom quartile ones).

Figure 3.1 below illustrates the research process followed by RT 233, which served as the panel of industry experts for the development of the Design Effectiveness research. The team began by exploring the state of current research on Design Effectiveness and the nature of current industry need. Once the updated DE definition and context distinction between DE and design management had been formulated, the team proceeded to hypothesize and scrutinize current practices that would ultimately be labeled as Design Effectiveness Practices – or DEPs. More than 40 hypothesized practices were ultimately screened and vetted down to the final listing of 30 DEPs.

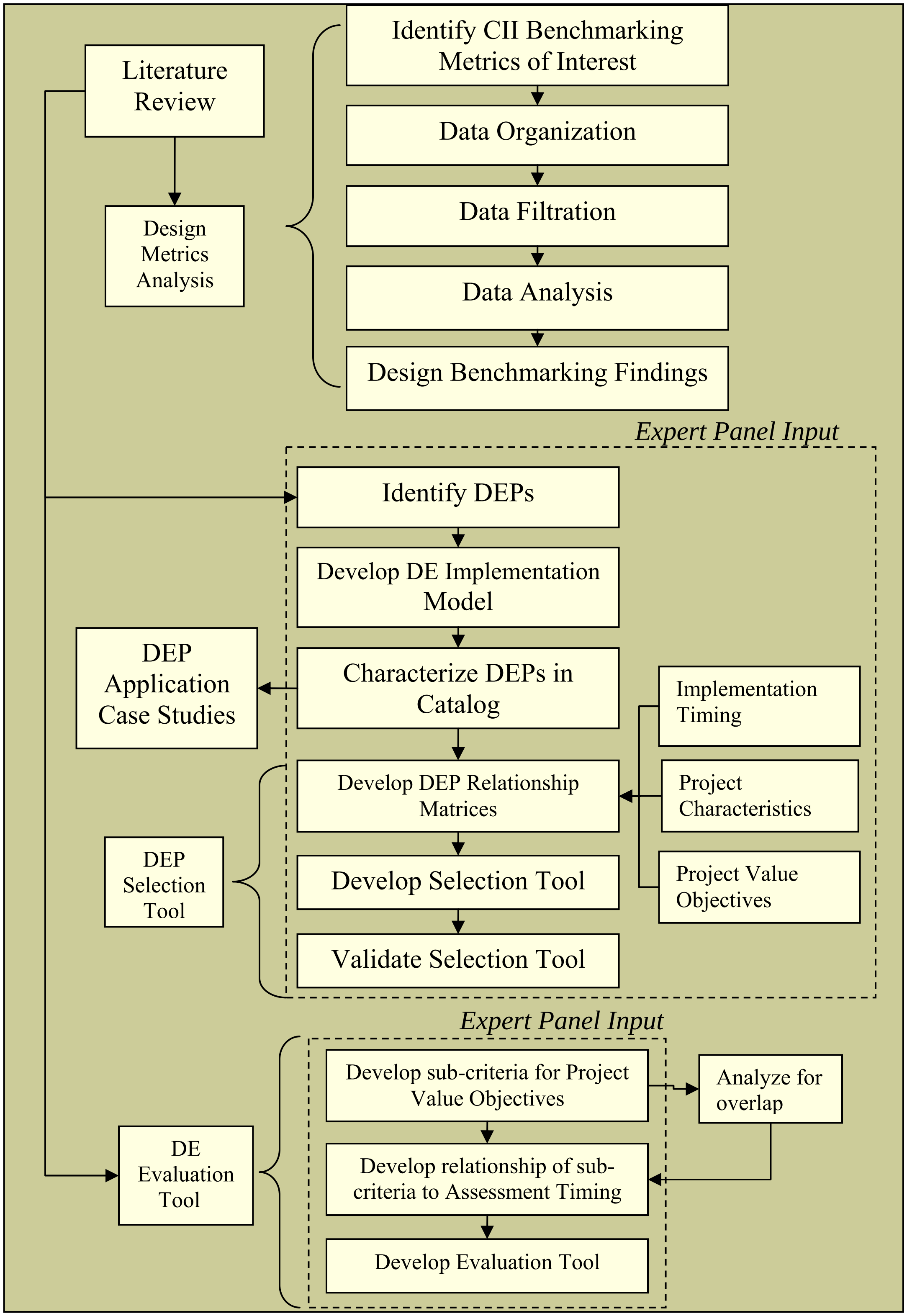


Figure 3.1: Methodology Overview

Next, an overall DE process framework or implementation model was developed and described both graphically and in words. Multiple iterations of process analysis through team discussions resulted in the model described in Chapter 2. Concurrently, a descriptive catalog of Design Effectiveness Practices was developed and structured with the use of a template of descriptive fields. This is described and provided in Appendix B. Recognizing the importance of DEP selection within the context of the implementation model, the team then focused on development of the DE Practice Selection Tool and all the practice characterization intelligence needed for that tool, such as DEP relationships with project value objectives, implementation timing, and leveraging project circumstances. The Excel®-based Selection Tool is described in Chapter 5 and the tool user manual is described in Appendix E. Details on validation of the Selection Tool on actual projects may be found in Chapter 6.

The team then devoted its efforts to updating the approach to Design Effectiveness evaluation. This was accomplished by using the 11 established project value objectives as the foundation for identifying DE evaluation criteria and sub-criteria. Timing of evaluation indications were also established for each sub-criteria in order to provide more guidance for implementation of evaluation. The DE evaluation criteria and sub-criteria are described in this chapter and provided in Appendix H. The DE Evaluation Tool is described in Chapter 7 and the tool user manual is provided in Appendix I. As with the original CII Design Effectiveness best practice, the DE evaluation methodology relies on the mechanics and assumptions associated with the Objectives Matrix methodology. These are reviewed in the previous chapter.

The research team's expert panel performed the following tasks:

- Identifying and screening DEPs
- Providing input on DEP Characterization Catalog
- Providing scores for the Timing, PVO, and Characteristics score matrices in the Selection Tool
- Provide the preliminary list of DE related sub-criteria.
- Provide input on the influence of the timing of evaluation on DE sub-criteria
- Internally and externally (through the expert panel of RT245) provide feedback for the validation of the DE sub-criteria.

The author performed the following duties:

- Benchmarking Data ANOVA Analysis
- Synthesizing and editing DEP Characterization Catalog
- Develop, test, validate, and provide application recommendations for the Selection Tool
- Develop, test, and update the DE Evaluation Tool
- Analyze the DE sub-criteria for interdependence

3.2 *Analysis of Design-Related Benchmarking Metrics:*

The purpose of this exploratory study was to gauge the effect of design on project performance. The steps in this process were identifying the metrics of interest, then organizing, filtering, and analyzing the data.

3.2.1 Identifying Metrics of Interest

Using the CII Benchmarking database, six dependent and seven independent variables were selected for analysis. The CII Database contained 1498 data entries from projects between 1990 and 2003. Table 3.1 presents the independent variables prior to filtration, while Table 3.2 presents the dependent variables, also prior to filtration. The "Cost % of PPP and Design" variable was not directly available from the CII database, and had to be derived by summing the Cost of Pre-Project Planning and Cost of Design, then dividing that total by the Total Project Cost. Similarly, the "Schedule % of PPP and Design" variable had to be derived by summing the durations of PPP and Design and dividing that by the Total Project Duration.

Table 3.1: Independent Variables Prior to Filtration

Independent Variable (CII Database label)	Description	Type	Scale	Available data (out of 1498)
Cost_PPP_Des_prct	Percentage of cost of PPP and design out of total cost	Interval	0-100%	312
Schd_PPP_Des_prct	Percentage of time of PPP and design out of total schedule	Interval	0-100%	455
perdsncn	Percent of Design complete by start of project	Interval	0-100%	684
quamgmt	Quality Management score	Interval	0-10	211
pdcs_DB	Project Delivery Method: DB or DBB type project	Nominal	0,1	1015
Renum_LS	Project Remuneration: Lump Sum or Cost Reimbursable	Nominal	0,1	284
Inc	Incentive (Negative, None, or Positive)	Nominal	-1,0,1	408

Table 3.2: Dependent Variables Prior to Filtration

Dependent Variable (CII Database label)	Description	Type	Scale	Available data (out of 1498)
Budgfact	Budget Factor = Total cost / (original + approved)	Interval	Varies about 1	1479
Shcdfact	Schedule Factor = Total duration / (original + approved)	Interval	Varies about 1	1436
scpfact	Scope Change Cost Factor = Cost of scope change / Project cost	Interval	0-1	104
scpsfact	Scope Schedule Factor = Scope time extension / Project duration	Interval	0-1	56
Rewfact	Rework cost factor = Cost of rework / project cost	Interval	0-1	547
Rewsfact	Rework Schedule Factor = Duration of Rework / Project duration	Interval	0-1	255

3.2.2 Data Organization and Filtration:

The data was categorized by "owner" and "contractor" projects for separate analysis. The data was then filtered for outliers and duplicates. Table 3.3 presents the logical limits set for outliers for independent and dependent variables.

Table 3.3: Outlier Filter Ranges

	Variable	Logical Range	Outlier Filter Range
Independent Variables	Cost % of PPP and design	0 < x < 1	> 0.5
	Schedule % of PPP and design	0 < x < 1	> 0.5
	Percent Design Complete	0 < x < 1	None needed
	Quality Management score	0 < x < 100	None needed
	Project Delivery System	Nominal	-
	Type of Remuneration	Nominal	-
	Use of Incentives	Nominal	-
Dependent Variables	Budget Factor	Varies about 1	< 0.5 or > 1.5
	Schedule Factor	Varies about 1	< 0.5 or > 1.5
	Scope Change Cost Factor	0 < x	> 0.5
	Scope Schedule Factor	0 < x	> 0.5
	Rework cost factor	0 < x	> 0.5
	Rework Schedule Factor	0 < x	> 0.5

After filtration, the Owner projects contained 473 data entries (Table 3.4 and Table 3.5). The independent variables had no data on the cost and schedule % of Pre-Project Planning and Design, and very little data on Quality Management, Type of Remuneration and Use of Incentives. Percent of Design Complete and Project Delivery System both had few missing data. The dependent variables also had some missing data, with Scope Change Cost and Schedule Factors missing in almost all entries, and Rework Schedule Factor missing several entries as well. Rework Cost factor has a few missing data entries, while Budget Factor and Schedule factor has very few missing entries.

Table 3.4: Owner Data Independent Variables after Filtration (473 Entries)

	Cost % of PPP and design	Schedule % of PPP and design	Percent Design Complete	Quality Management score	Project Delivery System	Type of Remuneration	Use of Incentives
Recorded	**0**	**0**	**335**	**29**	**300**	**29**	**50**
Missing	*473*	*473*	*138*	*444*	*173*	*444*	*423*
Min	-	-	2	0.25	0	0	-1
25%	-	-	50	3.38	-	-	-
50%	-	-	75	4.81	-	-	-
75%	-	-	95	6.45	-	-	-
Max	-	-	100	7.19	1	1	1

Table 3.5: Owner Data Dependent Variables after Filtration (473 Entries)

	Budget Factor	Schedule Factor	Scope Change Cost Factor	Scope Change Schedule Factor	Rework cost factor	Rework Schedule Factor
Recorded	**461**	**434**	**9**	**6**	**134**	**42**
Missing	*12*	*39*	*464*	*467*	*339*	*431*
Min	0.50	0.56	0.034	0.046	0.001	0.004
25%	0.85	0.92	0.036	0.050	0.014	0.013
50%	0.93	1.00	0.038	0.227	0.035	0.023
75%	0.99	1.06	0.045	0.472	0.076	0.046
Max	1.48	1.49	0.196	0.498	0.185	0.132

The Contractor Project data contained 340 data entries (Table 3.6 and Table 3.7). The independent variables contained a few missing data on Cost % of PPP and Design, even more missing data on Schedule % of PPP and Design, and almost no data on Percent Design Complete. However, similar to the Owner data, Project Delivery System had some missing data, while Quality Management, Type of Remuneration, and Use of Incentives had a considerable amount of missing data.

Table 3.6: Contractor Data Independent Variables after Filtration (340 Entries)

	Cost % of PPP and design	Schedule % of PPP and design	Percent Design Complete	Quality Management score	Project Delivery System	Type of Remuneration	Use of Incentives
Recorded	**141**	**34**	**1**	**25**	**233**	**45**	**50**
Missing	*199*	*306*	*339*	*315*	*107*	*295*	*290*
Min	0.00	0.13	58	2.41	0	0	-1
25%	0.10	0.38	58	3.96	-	-	-
50%	0.16	0.43	58	5.91	-	-	-
75%	0.23	0.48	58	7.15	-	-	-
Max	0.48	0.50	58	8.54	1	1	1

Table 3.7: Contractor Data Independent Variables after Filtration (340 Entries)

	Budget Factor	Schedule Factor	Scope Change Cost Factor	Scope Change Schedule Factor	Rework cost factor	Rework Schedule Factor
Recorded	**338**	**335**	**11**	**6**	**95**	**26**
Missing	*2*	*5*	*329*	*334*	*245*	*314*
Min	0.59	0.53	0.005	0.073	0.003	0.008
25%	0.91	0.94	0.020	0.092	0.015	0.030
50%	0.98	1.00	0.027	0.125	0.025	0.059
75%	1.01	1.03	0.078	0.206	0.049	0.105
Max	1.47	1.45	0.155	0.256	0.419	0.372

3.2.3 Data Analysis:

The data was analyzed using the Analysis of Variance (ANOVA) test. The test compared the dependent variables versus the independent variables, with the nominal variables being analyzed by halves and quartiles. A further detailed analysis of quartiles was also applied for interval data, and a Tukey's post-hoc test was conducted to identify the areas of significance. The criteria for significance were that the test had to contain more than 20 data points in the analysis, and produce a P-value less than 0.10.

3.3 *Identification of DEPs*

A total of 30 Design Effectiveness Practices (DEPs) were identified by RT 233. These practices were taken from many sources and examined by the expert panel for eligibility and applicability as a Design Effectiveness Practice. From an initial listing of 43 DEPs, 30 DEPs were approved by the panel while 13 did not meet the criteria for approval.

The 13 excluded DEPs and the expert panel's rationale were:

- Co-Location of Owner and Designer [Not really a process, but a condition]
- Piping Design Tools [Too narrow or limited in scope compared to other DEPs]
- On-Site Design [Rarely exclusively applied]
- Independent 3rd Party Review [Considered a subset of Design Quality Management DEP]
- Low Cost Design Centers [Considered a subset of Virtual Teams DEP]
- Lean Design Engineering [Not yet fully developed as a practice]
- Design for Globalization [Not optional in appropriate contexts]
- Dispute Prevention [Not fully evolved as a practice in context of design]
- Alignment / Team Building / Partnering [Considered part of Front End Planning, not design]
- Concurrent Engineering / Set-based Design [Less applicable on capital projects; most relevant to product design]
- FIAPP / XD / Building Information Models [Not yet fully developed as a practice]

- Early Feasibility Estimates [Most often a standard design process; not an optional practice]
- Pre-Project Planning [Considered a part of Front End Planning, not design]

The approved practices were then compiled as a list of effective measures used in design of all types of projects. Each practice has as its goal some improvement to the development and creation of a design or to enhance the design itself. The list was further validated by an external expert panel from CII RT245. Based on the external Expert panel's comments the list was updated accordingly. The practices were characterized in a list titled *Practices that Promote Design Effectiveness* which is included in Appendix C. However, before characterization could begin, the research set out to develop a general implementation model for the application of DEPs.

3.4 *Development of Implementation Work Process Model*

The Design Effectiveness Implementation Model was developed by the RT233 expert panel to provide guidance to organizations on how to set up and administer a Design Effectiveness (DE) program. The model was intended to promote efficient use of DE practices and tools on individual projects and continuous improvement of the organization's DE implementation. While the model was intended to be applicable to all industry sectors, it is anticipated that each organization would need to customize its features for their specific situation and needs.

Previous CII DE research concentrated on identification of DE input and output variables and quantitative evaluation of the effectiveness of designs. These functions were important steps in a design effectiveness effort. However, a more robust DE effort requires a comprehensive approach to DE program planning and implementation. The Design Effectiveness Implementation Model was developed to address these issues.

3.5 *Characterization of Design Effectiveness Practices:*

3.5.1 Overview:

After identifying the DEPs and setting up an implementation model, the research team went to characterizing the DEPs with the aid of the expert panel. Note that characterization is distinctly different from providing instructions on how to perform a practice. Instructions on how to perform the practices was not included in the scope of this research team. It is important to understand how the practices are characterized before listing the DEPs themselves. Therefore, each practice was explained by using the following 9 descriptors:

1. **Practice Objectives –** Each DEP has as its overall objective improving design effectiveness. This descriptor will explain how the practice improves effectiveness.

2. **Key Benefits –** The specific improvements that should result from proper application of the DEP.
3. **Influence on Project Value Objectives –** Eleven project values have been identified to evaluate which areas each DEP influences. These values are: Security, Operation and Maintenance Safety, Construction Safety, Regulatory and Standards Compliance, Capital Cost Reduction, Operation and Maintenance Efficiency, Product/Plant/Service Quality, Design and Construction Quality, Schedule Reduction, Environmental Stewardship, Flexibility for Future Use. The influence of each DEP on these values and its magnitude has been documented in a matrix which is included in this chapter.
4. **Practice History/Maturity –** The background history of each practice is discussed in this category.
5. **How Common –** A simple discussion of how much each practice is used in industry.
6. **Best Circumstances for Application –** Circumstances when benefits for the DEP are best leveraged.
7. **Limitations and Pre-Requisites –** Project conditions which should or should not be present during the application of the DEP. These might be team or design process conditions, or they might be the specifics needs of what is being designed.
8. **Linkage with Design Effectiveness** – This refers to how the DEP applies to the overall goal of Design Effectiveness. The linkage of a DEP might be design

productivity, an innovative strategy, design management, innovative implementation techniques, work processes, etc.

9. **References** – A listing sources available to help further define the DEP. This list should be used by the project team to learn more about a particular DEP and how to implement it on a project since detailed implementation of the practice is not included in this report.

Using the 9 descriptors above, a project team can better understand and evaluate whether the DEP can be applied to the project. It is important to note that the details of implementing any particular DEP need to be researched and developed by the project team. As noted above, the references available for implementing the DEP were included in the characterization. For projects with limited resources, the research team recommended that the DEPs should be scaled to meet the needs of the project. Skipping DEPs on smaller projects because of limited time or personnel was discouraged.

Three factors were identifies as influencing the suitability of a DEP: Desired Benefits, Timing, and Project Characteristics. To simplify benefit identification for each DEP, a *DEP Benefit/Tradeoff* matrix was developed. It listed specific project benefits (or Project Value Objectives), such as cost and schedule efficiency, with corresponding ratings for each DEP. Instances where a DEP impeded a benefit showed a negative correlation in the matrix. The *DEP-Timing* matrix illustrates the project phase in which application of the DEP gave the best chance for benefit. Finally, a list of *Best Circumstances for*

Application was developed to identify the characteristics under which DEPs would be best suited to be applied on a project. The three matrices were then used as the foundation to develop the Design Effectiveness Practices Selection Tool.

3.5.2 DEP-Project Value Objectives Matrix

The 30 different DEPs can have a range of influence on the performance of a project's project value objectives. As it is essential to understand how DEPs generally tend to affect projects, the research team developed a model portraying the probable impacts between the 30 DEPs and the 11 established Project Value Objectives. As shown in Table 3.9 below, the relationships are indicated as follows:

++ Significant positive impact,

+ Positive impact, and

– Negative impact.

The Negative impact was introduced to support the idea that some DEPs involve tradeoffs that mix positive and negative impacts on PVOs. For example, in some cases increased capital or operating cost is expended in order to achieve another important goal, such as schedule or safety. The relationships were developed using feedback from an expert panel on the research team. The expert panel divided the DEPs among themselves according to areas of expertise, and an initial round of relationship values was derived. The second round involved the entire expert panel in reviewing and assessing the relationships until consensus was reached on the overall relationship matrix. The relationships were later given numerical values for implementation as a Score Matrix in the DEP Selection Tool.

3.5.3 DEP-Implementation Timing Matrix

The relative impact on overall Design Effectiveness from the 30 DEPs also varies with timing of DEP implementation. It is important to recognize this, as this should be a consideration in the selection of DEPs for implementation. Accordingly, the research team modeled the impact-timing relationships of the 30 DEPs at three common design phase milestones:

- Start of Conceptual Design: 0% design complete
- Start of Early Detailed Design: 20% design complete
- Start of Late Detailed Design: 60% design complete

The values of the relationships were assigned by the expert panel in the same fashion used for the *DEP-Benefits* matrix. After individually assessing the relationships, the expert panel reviewed the overall matrix until consensus was reached on the values. The general concept of the matrix was the dwindling influence of DEPs in later project design phases.

3.5.4 Project Characteristics and Best Circumstances for DEP Application

In addition to understanding the benefits from DEP implementation and the timing of those benefits in selecting DEPs for a project, the research team identified that it is also very important to recognize those unique project characteristics that often “drive” the use of one or more DEPs. Accordingly, the research team, with the aid of the expert panel, identified and organized a listing of 94 project characteristics that leverage individual DEP benefits or act as best circumstances for application. The tradeoffs are categorized is the listing of *Best Circumstances for Application*, under Appendix D.

10 categories of circumstances were developed (listed as A through J). These categories summed up to 94 different project circumstances, with each project circumstance describing a situation that might apply to a project. The 94 characteristics paired with the 30 DEPs would essentially form the DEP-characteristics matrix for application in the DEP Selection tool, similar to the DEP-Benefits and the DEP-Timing matrices.

3.6 *DEP Selection Tool*

Given the complex and numerically intensive nature of processing the Score Matrices, the research team developed an implementation tool to sort through which DEPs were best suited for a project. The *DEP Selection Tool* combined the DEP score matrices mentioned earlier into an algorithm that would produce index scores for each DEP based on the selected Desired Benefits, Timing of the project, and selected Project Characteristics. The DEPs were then ranked to produce a list of recommended DEPs for implementation on the project. More details are provided in Chapter 5.

3.7 *Validation of DEP Selection Tool:*

3.7.1 Overview of Validation

The DEP Selection Tool was validated using a three-step set of surveys to compare program results to end-user input. The survey was sent out to 12 project managers, all with relatively design intensive projects (Water Treatment facilities, renovation, petroleum refineries, etc.). The first validation step used a survey to ask the participants to rank the DEPs appropriate to their respective projects based on intuition, then on a structured manual approach. The second step consisted of using the DEP Selection Tool to produce the DEP rankings for the project. The third step was a phone interview aimed at identifying the differences between the Structured Manual approach of the first survey step and the DEP Tool recommended rankings. The final step was combining the results of the surveys in an analysis to identify the overlaps in responses and gauge the reliability of the DEP Selection Tool in identifying the appropriate DEPs.

3.7.2 Manual Approach

The first step in the validation process focused on identifying the DEPs that the participants would find appropriate for their projects (see Appendix F for a sample survey). After filling in their contact information and a brief description about their project, participants were given a list of 30 DEPs and asked to identify the DEPs they were familiar with; all other DEPs would be excluded from the analysis. With the selection pool established, the participants were asked to rank the top 10 DEPs that they intuitively think are appropriate for their project. The survey then proceeded into the structured manual approach.

The structure manual approach aimed to provide the participants with a logical and structured method to manually ranking the DEPs. The process began by asking the participants to identify the desired benefits on the project. This section consisted of the participants identifying each of the 11 Project Value Objectives as of "Not Applicable", "Low", "Medium", or "High" importance to their projects. The survey set then proceeded to ask the participants to list the DEPs (from the selection pool previously established) that best suit the desired benefits identified. The next step in the structured manual approach asked the participants to indicate current phase of the project from three options: Start of Conceptual Design, Start of Early Detailed Design, and Start of Late Detailed Design. The participants were then asked to list the DEPs that would best suit the project given the phase selected. The third part of the structured manual approach asked the participants to list the DEPs that would best respond to the unique characteristics or challenges on the project, and identify those characteristics or challenges. The last part of the structured manual approach asked the participants to rank the top 10 DEPs for their projects based on the DEPs identified in the previous three steps. With the first step of the survey completed, the participants were asked to return the document and were then sent the DEP Selection Tool as the second step of the validation process.

3.7.3 Automated Approach

The second part of the validation involved sending the DEP Selection tool to respondents of the manual survey. The participants were asked to fill out the selection tool using the same project used in the manual survey. The DEP Selection Tool followed the same steps used in the structured manual approach to identify the desired benefits, project phase, and unique project characteristics based on a selection pool of DEPs selected by the participant. The Selection Tool, however, contained its own algorithms and matrices for automatically identifying and ranking appropriate DEPs for the project. The participants were then asked to return the saved results of the Selection Tool and a phone interview was scheduled to identify the differences between the Structured Manual approach and the Selection Tool rankings.

3.7.4 Phone Interview

The aim of the phone interview was to identify the reason behind the discrepancies in rankings between the structured manual approach and the selection tool. The phone interview consisted of reviewing each of the top 10 ranked DEPs in the Selection Tool results and the Structured Manual approach with the corresponding participant and assessing the appropriateness of the ranking. See Appendix G for an interview guide sample.

The first part of the interview focused on assessing the ranking of the DEPs recommended by the Selection Tool. The participants were asked to identify the appropriateness of each of the 10 DEPs ranked by the tool based on the following options:

a) This DEP was deliberately excluded from the analysis
b) I am not familiar with this DEP
c) Recommended DEP is not appropriate because…
d) Recommended DEP is appropriately ranked
e) Recommended DEP is appropriate for project but with a different rank.

The participants were also asked to clarify the reasoning behind their choice of one of the five options.

The second section of the phone interview asked the participants to assess their selection of the DEPs in the Structured Manual approach. This section of the interview reviewed each of the top 10 ranked DEPs by the participants in the first survey of the validation. The participants were asked to assess each of their DEPs as:

a) DEP should remain a high priority for the project
b) DEP is OK for the project, but not a top 10 DEP
c) This DEP should not have been selected at all

Finally, the participants are asked to provide feedback on what advantages, disadvantages, and suggestions they had for the DEP selection tool. The participants were also asked which of the three processes of DEP selection they preferred: the intuitive method, the Structured Manual approach, or the DEP Selection Tool

3.7.5 Analysis of Responses

The analysis of responses was divided into two steps. The first involved comparing the rankings matching between the Structured Manual approach and the DEP Selection Tool. The second step of the analysis used the phone interview to determine whether the tool recommended rankings meet the user needs and expectations.

First step of analysis compared the rate of matching and consistency between the DEP rankings of the Structured Manual approach and the recommended DEP Selection Tool. The initial criteria used defined as:

- Top 10 Match (Manual-to-Tool): The proportion of the top 10 DEPs from the Structured Manual approach that were also ranked among the top 10 DEPs recommended by the Tool.
- 4-ranks' Consistency (Manual-to-Tool): The proportion of the matched DEPs with a difference of 4 or less ranks between them.

Since there is no "absolute true" ranking of DEPs, the matching analysis only serves to provide a comparison of how closely the DEP Selection Tool rankings resemble a rankings developed through a structure manual analysis process. Only by asking the participants themselves about their preferred rankings between the two can one identify the most suitable DEP ranking. Thus a second pair of criteria for matching and consistency would be:

- Top 10 Match (Tool-to-user): The proportion of the top 10 DEPs recommended by Selection Tool that the user assessed as appropriate.
- 4-ranks' Consistency (Tool-to-user): The proportion of the matched DEPs recommended by the tool that the user assessed as appropriately ranked within a deviation of 4 or less ranks.

To achieve this, the second step of the validation analysis involved using the ranking assessments inquired in the phone interview to identify the reliability of the DEP Selection Tool rankings. The following thresholds were established based on the previous similar work (Heesung Cha, 2003), which used a 70% threshold for both criteria. Due to the tight scoring nature in the DEP Selection Tool, the consistency rate was lowered but the match rate increased. Some DEPs shared similar score patterns in the Score Matrices (Ex: Design for Operational Automation, Design for Operational Safety, Design for People in the PVO Score Matrix). With the sacrifice of the consistency of 1 of the top-10 DEPs to capture 1 more matching DEP in the top-10 list, the following validation criteria were derived:

- Usefulness of Tool: 80%
- User Familiarity with Project: 80%
- Tool Preference (versus other selection methods): 80%
- 80% Top-10 Match rate (Manual-to-Tool and Tool-to-User)
- 60% 4-ranks' Consistency rate (Manual-to-Tool and Tool-to-User)

3.8 *Development of DE Evaluation Criteria and Tool*

The research team set out to develop the Design Effectiveness process of the Implementation plan in more detail and to focus on developing an application tool to help streamline the process of evaluation. The research team began by listing evaluation sub-criteria for the PVOs, then identifying the impact of the timing of the implementation on the sub-criteria. The team then proceeded to analyze each of the sub-criteria for interdependencies. The interdependency analysis was conducted by the author, and the results were presented to the expert panel for input on editing the sub-criteria. After the expert panel had updated the sub-criteria list, it was sent for external validation by the expert panel on RT245. Using the feedback of the two expert panels, the author updated the interdependence analysis. Although many interdependencies were eliminated, some remained but were not quite serious for the purposes of the DE Evaluation tool (See Appendix J). Finally, the author developed an application tool to help implement the DE evaluation process in a more streamlined method.

The first level of DE criteria is the Project Value Objectives (PVO) themselves. These serve as the major categories of all project outcome parameters (or sub-criteria). Thus, the entire DE evaluation approach was designed to be PVO-driven. The research team developed the sub-criteria under each PVO to reflect the element of design performance being evaluated. The sub-criteria were designed to be specific characteristics with measurement scales that together formed a tool to facilitate DE evaluation. Figure 3.2 provides an example of PVO and Sub-Criteria.

The Project Value Objective of O&M Efficiency, from a design effectiveness perspective, can be measured by one or more of the eight sub-criteria as shown in Figure 3.2. To the extent that the selected sub-criteria are successfully met or achieved, the overall PVO of O&M Efficiency is also achieved.

The next step in developing the DE Evaluation Process was factoring in the implementation timing for each sub-criterion. The timing milestones shown in the assessment sub-criteria table are used to indicate the project timing at which a given sub-criteria can be evaluated. These are numbered 1 through 5 and represent the following project stages:

1. Conceptual Design: 20 percent design complete
2. Detailed Design: 60 percent design complete
3. Design 100 percent complete
4. Construction complete
5. Post Occupancy Evaluation

With the timing of implementation accounted into the process, the team focused on cross-analyzing all of the sub-criteria of interdependencies. This step allowed an iteration of reviews for most sub-criteria and lead to a more independent set of sub-criteria. The analysis was done by examining each sub-criterion against all the rest in a matrix form.

Each sub-criteria pair-wise interaction was assessed on a 1-10 scale of dependency, and the sub-criteria that were graded with a score of 7 or higher were put under review by the team included in the tool to assist users in avoiding duplication in sub-criteria (which would violate one of the basic premises of the objectives matrix methodology). After review by the RT245 expert panel, the interdependency table was updated according to the new sub-criteria they provided. Although many interdependencies were eliminated, some still persisted. The updated interdependency matrix in provided in Appendix J.

The assessment scale of the DE Evaluation sub-criteria was given on a 0-10 Likert scale, with the limits of the scale defined for user clarification (See example in Figure 3.2). Since it is possible to not use all sub-criteria, the evaluation process may exclude the sub-criteria that do not apply. This helps avoid skewing the evaluation score by scoring inapplicable criteria as “0”. All PVO criteria and supportive sub-Criteria are provided in their entirety in Appendix H.

The Evaluation process was designed on the basis of the Objectives Matrix. The scoring of sub-criteria (of a given PVO) would be weighted, and the resulting weighted average would be the PVO Evaluation score. Similarly, the weighted average of the PVO scores would produce the overall project Design Effectiveness score. Due to the subjective nature of the evaluation process, and given the unique nature of most construction projects, the research team opted to give the evaluators ample flexibility by allowing them to set their own PVO weight and sub-criteria weights. Given the numerically intensive nature of this exercise, the research team opted to develop an application tool for this process. The tool is described in greater detail in Chapter 6.

6	**O&M Efficiency**												**Timing**				
6.1	**Higher efficiency of energy consumption relative to peer facilities**												1	2	3	4	5
		MUCH LOWER			LOWER				HIGHER			MUCH HIGHER				x	x
		0	1	2	3	4	5	6	7	8	9	10					
6.2	**Design facilitates minimal facility life-cycle cost (total cost of ownership)**												1	2	3	4	5
		DOES NOT			SOMEWHAT				MOSTLY			DOES					x
		0	1	2	3	4	5	6	7	8	9	10					
6.3	**Design maximizes asset demand utilization (or facility availability factor)**												1	2	3	4	5
		DOES NOT			SOMEWHAT				MOSTLY			DOES					x
		0	1	2	3	4	5	6	7	8	9	10					
6.4	**Higher production raw material yield efficiency relative to peer facilities**												1	2	3	4	5
		MUCH LOWER			LOWER				HIGHER			MUCH HIGHER				x	x
		0	1	2	3	4	5	6	7	8	9	10					
6.5	**Lower annual unit cost of maintenance/repair relative to peer facilities**												1	2	3	4	5
		MUCH HIGHER			HIGHER				LOWER			MUCH LOWER					x
		0	1	2	3	4	5	6	7	8	9	10					
6.6	**Lower annual operator hours/units relative to peer facilities**												1	2	3	4	5
		MUCH HIGHER			HIGHER				LOWER			MUCH LOWER					x
		0	1	2	3	4	5	6	7	8	9	10					
6.7	**Higher annual occupant/operator productivity relative to peer facilities**												1	2	3	4	5
		MUCH LOWER			LOWER				HIGHER			MUCH HIGHER					x
		0	1	2	3	4	5	6	7	8	9	10					
6.8	**Lower waste disposal cost relative to peer facilities**												1	2	3	4	5
		MUCH HIGHER			HIGHER				LOWER			MUCH LOWER					x
		0	1	2	3	4	5	6	7	8	9	10					

Figure 3.2: Sub-Criteria for the O&M Efficiency Project Value Objectives

3.9 *Development of DEP Application Case Studies*

To better cement the application of DEPs, the research team provided 3 case studies on Design Effectiveness Practices. The purpose of the case studies was to provide the reader with a real-world example of the application, along with guidelines for implementation and the results of implementing the DEP. The case studies first discussed the benefits of the DEP application and the overall method of application, then continued to provide the specifics and details of the case study.

The first case study discusses the application of Standard Design Delivery Process on a water pollution control project in Atlanta. The second case study discusses the way the CH2M HILL construction company applies a Design Productivity Tracking system for its projects. The third case study discusses the application of Design for Constructability and Design for PPMOF on an aluminum production facility in Iceland. Please see Appendix A for details.

Chapter 4:

Analysis of Design-Related Benchmarking Metrics

4.1 *Owner Data Results*

Due to the limitations in the data (recall Table 3.4 and Table 3.5), the analysis of the Owner data set produced very limited results. The absence of "% of PPP and Design" (Cost and Schedule) data after filtration, coupled with little data on "Quality Management", "Type of Remuneration", and "Scope Change Factors" (Cost and Schedule) left very little data for analysis.

The only significant finding was the effect of "project delivery system" on "rework cost factor". Figure 4.1 illustrates the result of the ANOVA analysis, where the set contained 95 data points and produced a P-value of 0.008. The analysis indicates that Design-Build (DB) projects tend to have less Rework Cost that Design-Bid-Build (DBB) projects. Table 4.1 shows the overall results of the analysis for the Owner data.

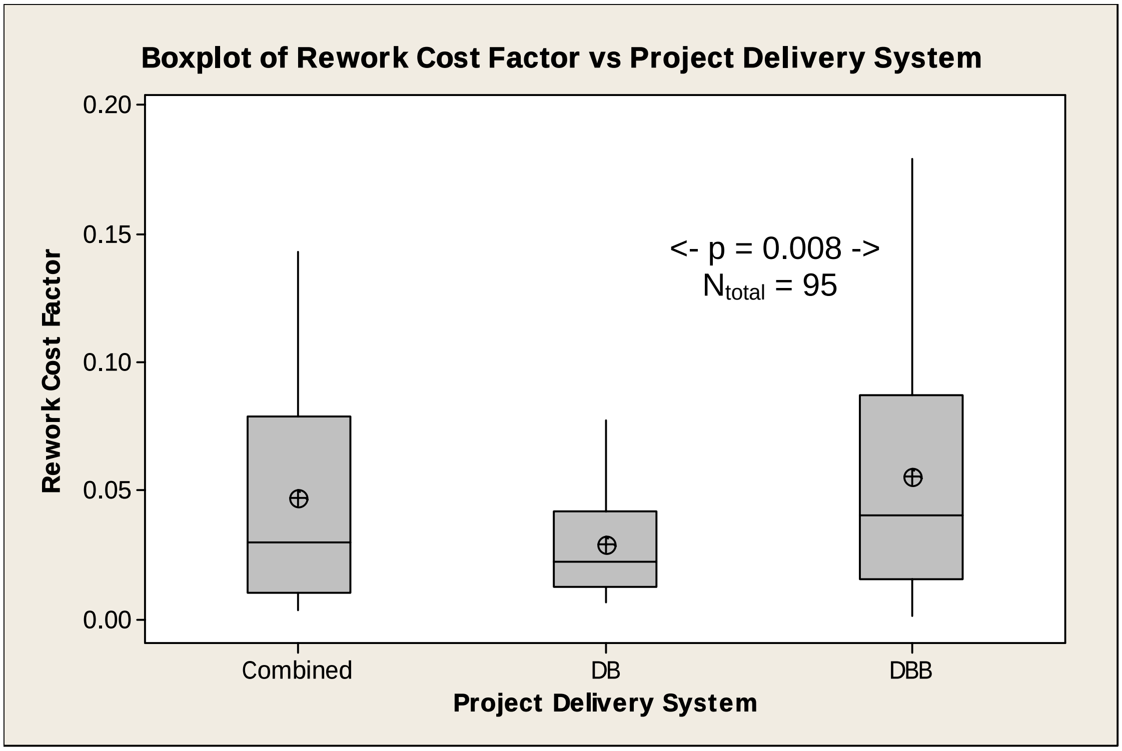


Figure 4.1: Owner: Rework cost factor vs. Project delivery system.

Table 4.1: Overall results of the Owner data set analysis.

Independent Variables

Dependant Variables	Cost % of PPP and design	Schedule % of PPP and design	Percent Design Complete	Quality Management score	Project Delivery System	Type of Remuneration	Use of Incentives
Budget Factor							
Schedule Factor							
Scope Change Cost Factor							
Scope Change Schedule Factor							
Rework cost factor					✓ DB		
Rework Schedule Factor							

DB = Design-Build type projects have a better (lower) rework factor

4.2 *Contractor Data Results*

The Contractor data set suffered from some limitations (recall Table 3.6 and Table 3.7), but fared better than the Owner data set in the analysis. There was no data on "Percent Design Complete", and almost none on Scope Change factors (cost and schedule). There was also little data on "Schedule % of PPP and Design", "Quality Management", and "Rework Schedule factor".

The main significant finding of this analysis was the analysis between "Budget Factor" and "Cost % of PPP and Design". There was significance between 1st and 3rd quartiles of "Budget Factor", where the analysis of 141 data points produced a p-value of 0.002 (Figure 4.2). There was also significance between Top and Bottom Halves of Budget Factor with a p-value of 0.006 (Figure 4.3). The reverse analysis showed significance between Top and Bottom quartiles of "Cost % of PPP and Design", at a p-value of 0.036 (Figure 4.4). This indicates that the higher the "Cost % of PPP and Design", Lower the "Budget Factor".

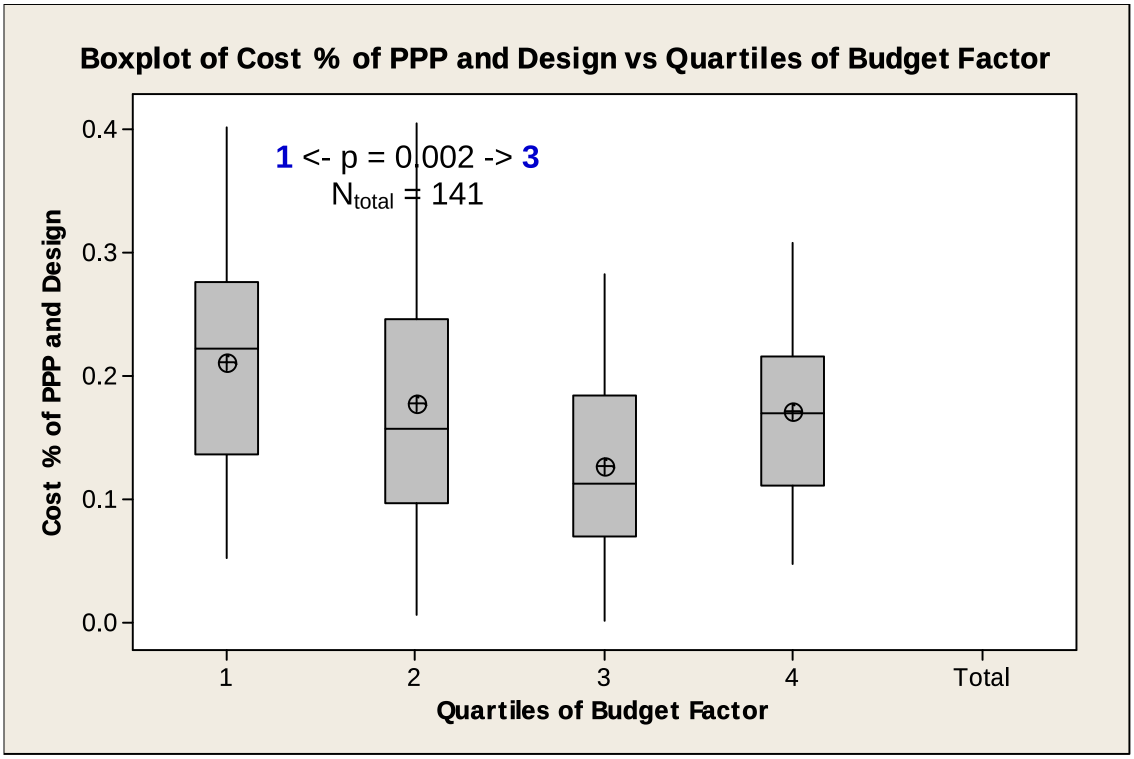


Figure 4.2: Contractor: "Cost of PPP and Design" vs. Quartiles of "Budget Factor"

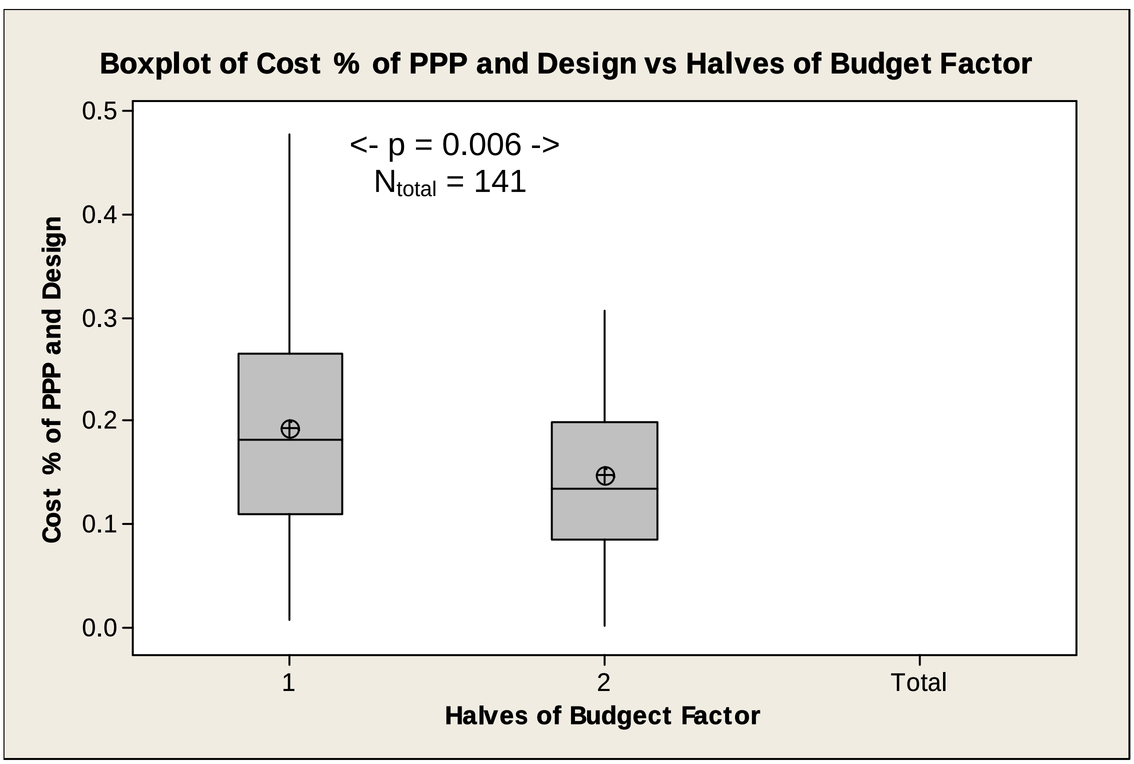


Figure 4.3: Contractor: "Cost % of PPP and Design" vs. Halves of "Budget Factor"

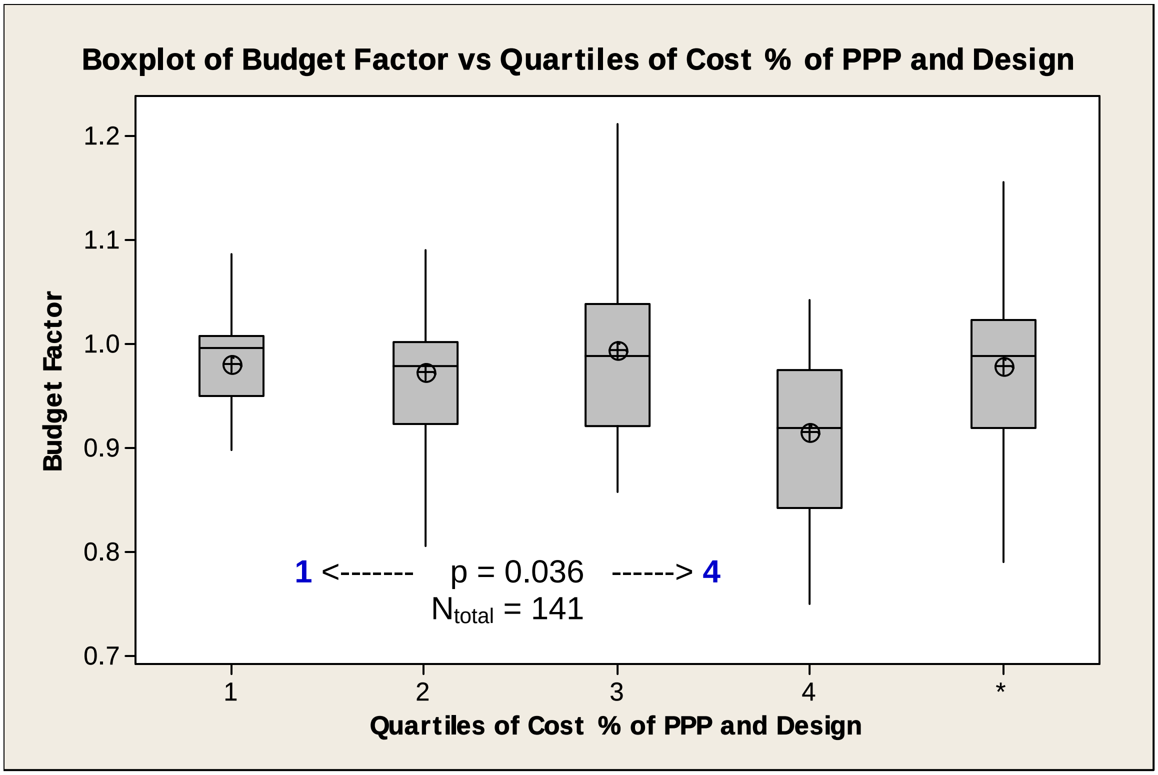


Figure 4.4: Contractor: "Budget Factor" vs. Quartiles of "Cost of PPP and Design"

Other results of the analysis of the contractor data set indicate significance between "Budget Factor" and "Project Delivery System", where DBB projects tend to have a lower Budget Factor. The analysis of 234 data points produced a p-value of 0.031 (Figure 4.5). Another result was the significance between "Budget Factor" and the use of incentives. The analysis of 51 data points indicated that positive incentives produced a lower budget factor with a p-value of 0.035 (Figure 4.6). Table 4.2 shows the overall result of the analysis for the Contractor data set.

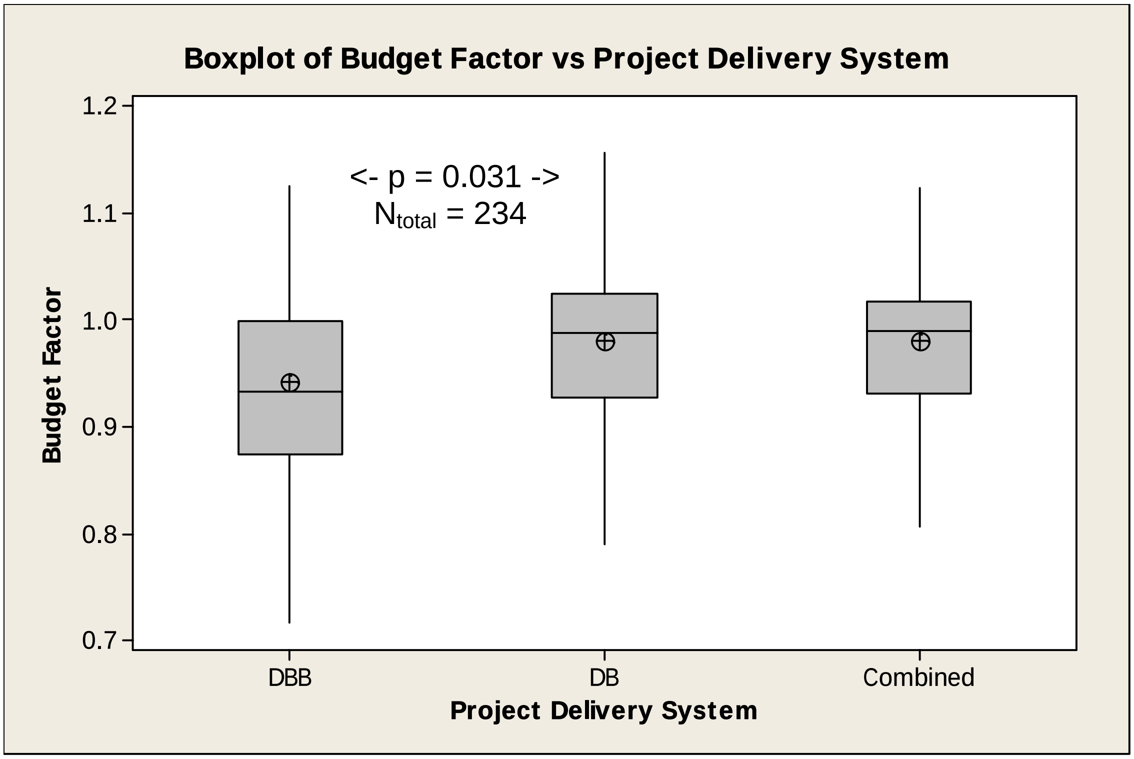


Figure 4.5: Contractor: "Budget Factor" vs. Project Delivery System

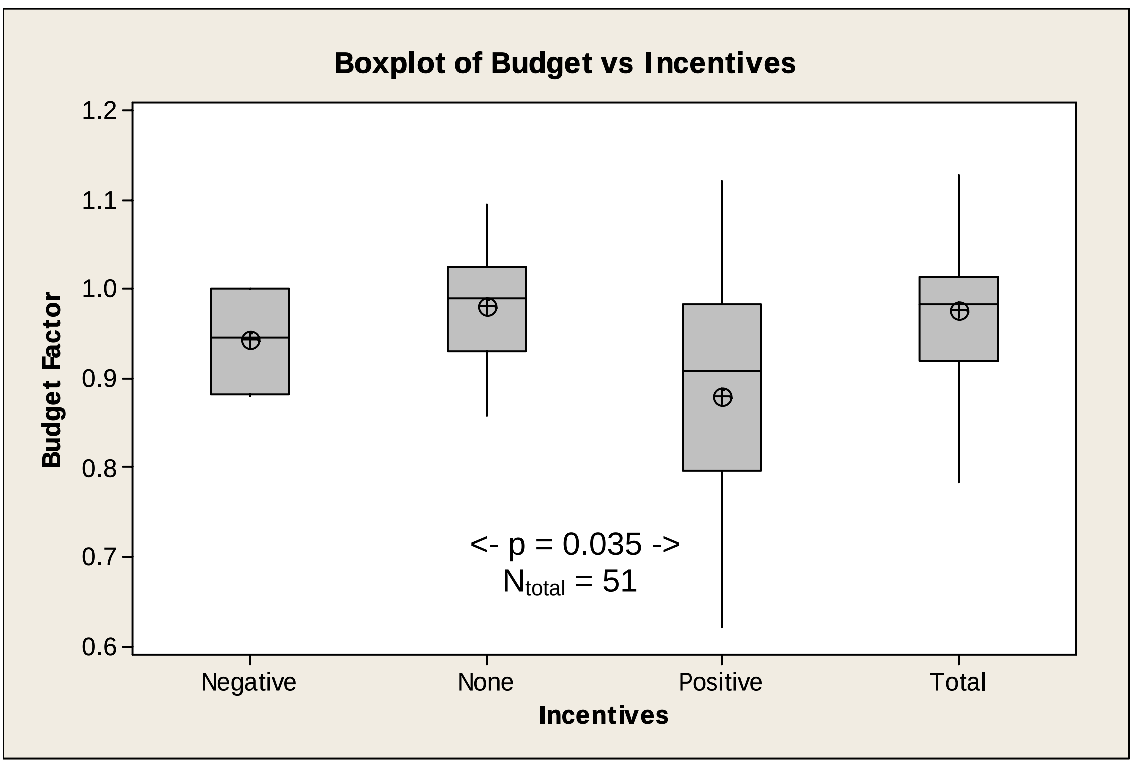


Figure 4.6: Contractor: "Budget Factor" vs. "Incentives"

Table 4.2: Overall results of the Contractor data set analysis

		Independent Variables						
		Cost % of PPP and design	Schedule % of PPP and design	Percent Design Complete	Quality Management score	Project Delivery System	Type of Remuneration	Use of Incentives
Dependant Variables	Budget Factor	✓ inv				✓ DBB		✓ +
	Schedule Factor							
	Scope Change Cost Factor							
	Scope Change Schedule Factor							
	Rework cost factor							
	Rework Schedule Factor							

DBB = Design-Bid-Build projects have a better (lower) Budget Factor
+ = Positive Incentives produce a better (lower) Budget Factor
Inv = inverse relationship

Chapter 5: DEP Selection Tool

5.1 *Overview of Implementation Work Process Model*

The research team set out to develop a Design Effectiveness Implementation Work Process Model to guide to provide guidance to organizations on how to set up and administer a Design Effectiveness (DE) program. The process was based off of the general strategy of Preparing, Planning, Implementing, Evaluating, and Improving.

The DE Implementation model is shown in Figure 5.1. The process is carried out on two levels, the organizational level and the project level. At the organizational level, during the first phase the DE program is established and maintained. At the project level, during phases two, three and four the DE program is integrated into the project plan, implemented, and evaluated. DE effort evaluation is then brought back to the organizational level during phase five, where it is documented and integrated into the organization's DE knowledge base for application on future projects.

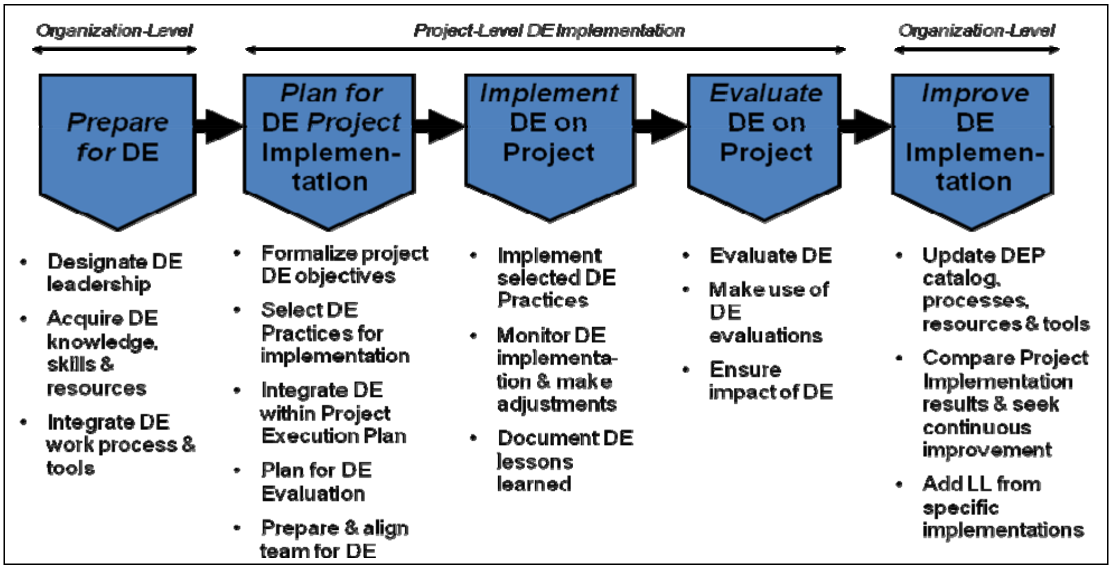


Figure 5.1: Design Effectiveness Implementation Process Model

5.2 *DEP Selection Tool Matrices*

In forming the list of 30 DEPs, the research team split the practices into two categories: "Design Strategies and Management" and "Opportunity Capture/Design for X" (see Table 5.1). "Design Strategies and Management" practices were identified as those that improve overall design efficiency. They concentrate on the design team and the work processes to get the design done more effectively. Management of the design process, lessons learned, and software were included here. These practices were classified as improving the work processes rather than improving the design in a specific area.

The "Opportunity Capture/Design for X" category included the practices that improve design in specific areas. Energy efficiency, safety, schedule and others make up this category. DESs in this category focus on improving one aspect of a design and therefore require certain circumstances for success. These circumstances were called out in the description of each DEP. Tradeoffs or timing requirements were also noted so that the application of a DEP can be tailored to the right phase of a project while minimizing the adverse effects on other aspects of the design. In some cases, increased capital or operating cost is balanced against another important goal such as schedule or safety.

Table 5.1: Design Effectiveness Practices

DESIGN STRATEGIES & MANAGEMENT	
1.	Standard Design Delivery Process
2.	Design Quality Management/QA/QC
3.	Design Standardization/Process Industry Practices
4.	Lessons-Learned System/ Learning Organization Approaches
5.	Change Management
6.	Design Productivity Tracking
7.	3D & 4D CAD
8.	Design Automation & Software
9.	Virtual Teams
10.	Technology Tracking & Selection
OPPORTUNITY CAPTURE/ DESIGN FOR X	
11.	Design for Constructability
12.	Design for Construction Automation
13.	Design for Construction Safety
14.	Design to Cost
15.	Design for Energy Efficiency
16.	Design for Expandability
17.	Design for Maintainability
18.	Design for Operational Automation
19.	Design for Operational Safety
20.	Design for People
21.	Design for PPMOF
22.	Design for Reliability
23.	Design for Schedule Performance
24.	Design for Security
25.	Design for Startup
26.	Design for Sustainability
27.	Design to Capacity
28.	Risk-Based Design
29.	Value Engineering In Design
30.	Vendor Integration & Design for Supply Chain

5.2.1 DEP-Project Value Objectives Matrix

The research team developed a model portraying the probable impacts between the 30 DEPs and the 11 established Project Value Objectives. As shown in Table 5.2 below, the relationships are indicated with ++, +, and a – symbol. Some DEPs involve tradeoffs that mix positive and negative impacts on PVOs. For example, in some cases increased capital or operating cost is expended in order to achieve another important goal, such as schedule or safety. The relationships were given numerical values for implementation as a Score Matrix in the DEP Selection Tool. The numerical values were as follows:

++	Significant positive impact (+1.0)
+	Positive impact (+0.5)
–	Negative impact (-0.25)

5.2.2 DEP-Implementation Timing Matrix

The research team modeled the impact-timing relationships of the 30 DEPs at three common design phase milestones:

- Start of Conceptual Design: 0% design complete
- Start of Early Detailed Design: 20% design complete
- Start of Late Detailed Design: 60% design complete

Table 5.2: Project Value Objectives Impacts on DEPs

[redacted]

The general concept of the matrix was the dwindling influence of DEPs in later project design phases. Table 5.3 demonstrates the decline of DEP influence on a 0-5 scale. This scale was converted to a 0-10 scale for implementation as an score matrix in the DEP Selection Tool.

Table 5.3: Influence of Timing factor on DEPs

[redacted]

5.2.3 Project Characteristics and Best Circumstances for DEP Application

The research team identified and organized a listing of 94 project characteristics that leverage individual DEP benefits or act as best circumstances for application. The tradeoffs are categorized is the listing of *Best Circumstances for Application*, under Appendix D.

10 categories of circumstances were developed (listed as A through J). These categories summed up to 94 different project circumstances, with each project circumstance describing a situation that might apply to a project. In using the listing, a project team would read through and identify which circumstances apply and note the DEP associated with the circumstance. The associated DEP is identified by the number or numbers in parenthesis shown with the circumstance. An example is "Project team is large and complex (5) (8)". A project manager with a large and complex team would note that DEPs 5 (Change Management) and 8 (Design Automation and Software) would help.

The 94 characteristics paired with the 30 DEPs would essentially form the DEP-characteristics matrix for application in the DEP Selection tool, similar to the DEP-Benefits and the DEP-Timing matrices. However, to truly produce such a matrix, each relationship would have to be scored in an objectives matrix. Given the size of the matrix at hand, the research team opted to treat each characteristic as equal relative to all the characteristics that contributed to a given DEP. However, since each DEP corresponded to a different number of characteristics (between 4 and 8), the research team used a radical equation (see Figure 5.2) to adjust the number of selected characteristics per total. The formula's aim was to adjust for the difference in missing a characteristic for a DEP with 4 characters (3/4 characteristics) and a DEP with 8 characteristics (7/8 characteristics).

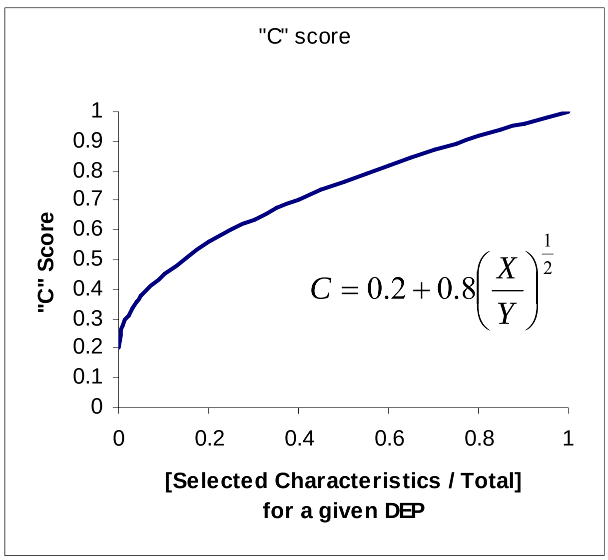


Figure 5.2: Project Characteristics transformation formula

5.3 *Selection Tool Purpose and Benefits*

The Excel™ based DEP Selection Tool was developed by the research team to facilitate the selection of Design Effectiveness Practices for implementation on a project. The tool gives consideration to all 30 DEPs previously discussed and takes into consideration three primary selection factors or criteria:

- Current project phase (for timing of implementation);
- Desired or targeted project benefits and their relative importance; and
- Project-specific characteristics, which are sometimes referred to as "circumstances for leveraged application".

The purpose of this selection tool is to provide guidance on which DEPs may offer the most value for a project. Team judgment is still required; the results are intended to initiate a team dialog on which DEPs should be given serious consideration for implementation. Appendix E of this document contains a detailed *User Manual* for the DEP Selection Tool.

5.4 *Selection Tool Logic*

Selection Tool logic is based on consideration of the following types of information:

- Timing of DEP implementation (by project phase). This is a reflection of the erosion of DEP benefits from late implementation as the project progresses.
- Desired benefits from DEP implementation. These are established through a project-specific prioritization of the 11 different Project Value Objectives.
- Pre-screening of DEPs, if desired, to eliminate unfamiliar or unavailable DEPs from further consideration.
- Characterization of the project. This is based on analysis of 94 structured statements that link DEPs with conditions for leveraging their benefit.

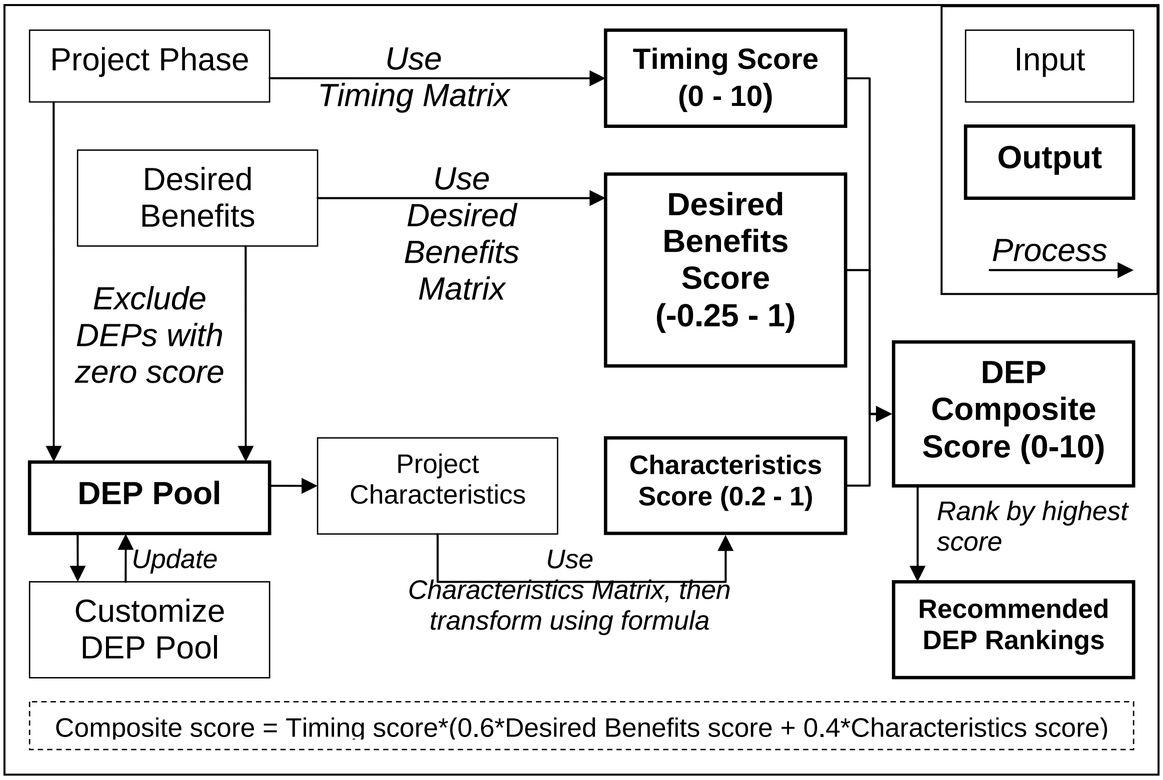


Figure 5.3: DEP Selection Tool Logic

A chart of the selection tool logic is presented in Figure 5.3. The process begins by asking the user to input the Project Phase. This information is processed through the Timing Objective Matrix and a Timing Score for each DEP is calculated (but not yet displayed to the user). The user is then given the option to identify project desired benefits and/or exclude DEPs from the analysis. If the user skips the desired benefits selection process, all the desired benefits are scored equally. The Desired Benefits score is then derived from the Desired Benefits Score Matrix. However, if the user identifies some desired benefits as more important than others, then the Desired Benefits Score would be adjusted through a normalized multiplier for each score.

Given the user input up to this point, an initial DEP Pool is formed by excluding DEPs from the available list of 30 DEPs. The excluded DEPs are those that have a zero score from the Timing Matrix or Desired Benefits Matrix, as well as DEPs that are intentionally excluded by the user from the analysis. The DEP Pool is then presented to the user for review. The user may customize this pool by including or excluding DEPs. Once the user is satisfied with the DEP Pool, the project characteristics list is formed from only the DEPs in the DEP Pool; Characteristics that pertain only to all the excluded DEPs are not needed and therefore not presented. The user indicates which characteristics apply to the project, and the information is then processed through the Characteristics Matrix to count the number of characteristics (out of total that apply) per DEP. This is then used in a transformation formula for purposes of adjustment to produce the Characteristics Score.

The DEP Composite Score is then derived for each DEP in the DEP Pool by multiplying the Timing Score with the weighted average of the Desired Benefits and Characteristics Scores (0.6 and 0.4 weights, respectively). The DEP pool is then ranked by highest Composite Score, and this is color-coded into “Highly Recommended”, “Recommended”, and “Not Very Recommended” categories for the project based on Composite Score.

Further details on the Tool’s algorithm are available in the DEP Selection Tool User Manual (Appendix E).

5.5 *Selection Tool User Interface*

5.5.1 DEP Pre-screening

The Selection Tool features a robust filtering system that can screen DEPs from the selection process based on user inputs (Figure 5.4). The program allows the users to specifically include or exclude DEPs from consideration (Figure 5.5).

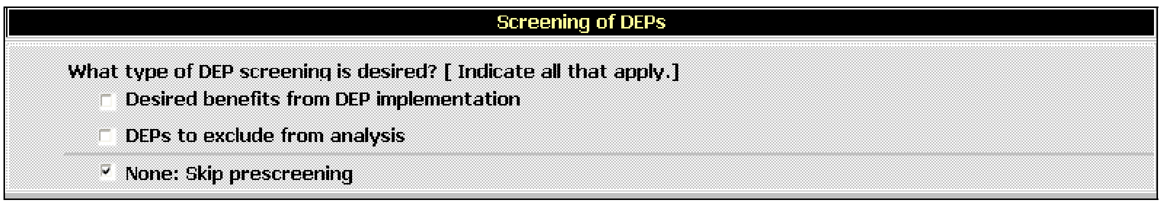


Figure 5.4: User-defined Screening Parameters

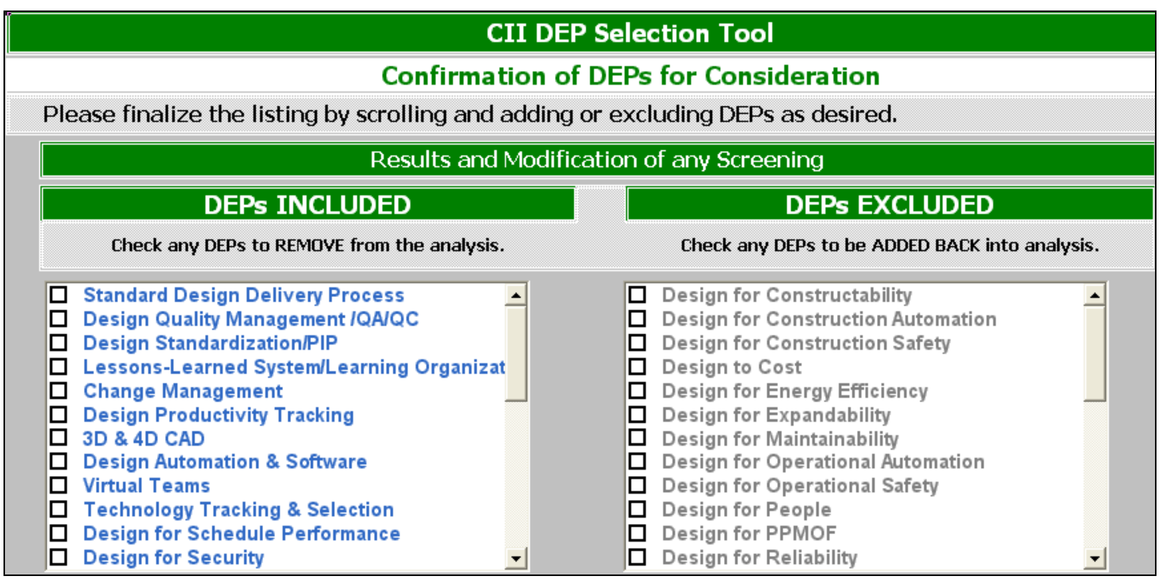


Figure 5.5: Screening DEPs from Consideration

5.5.2 Consideration of Project Timing, Objectives, and Characteristics

The Selection Tool considers DEP implementation timing relative to major design phase milestones (Figure 5.6), project value objectives (Figure 5.7), and project characteristics (Figure 5.8) in the selection process.

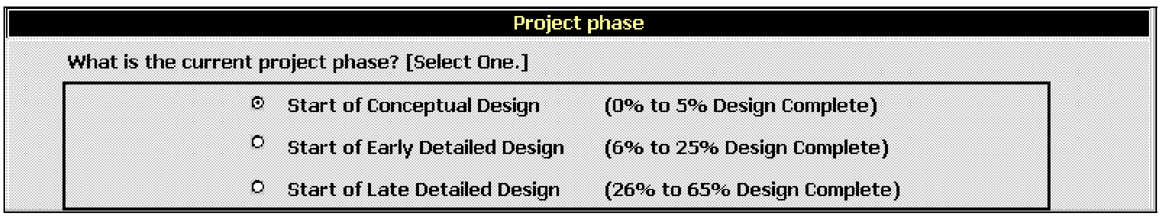


Figure 5.6: Timing of DEP Implementation

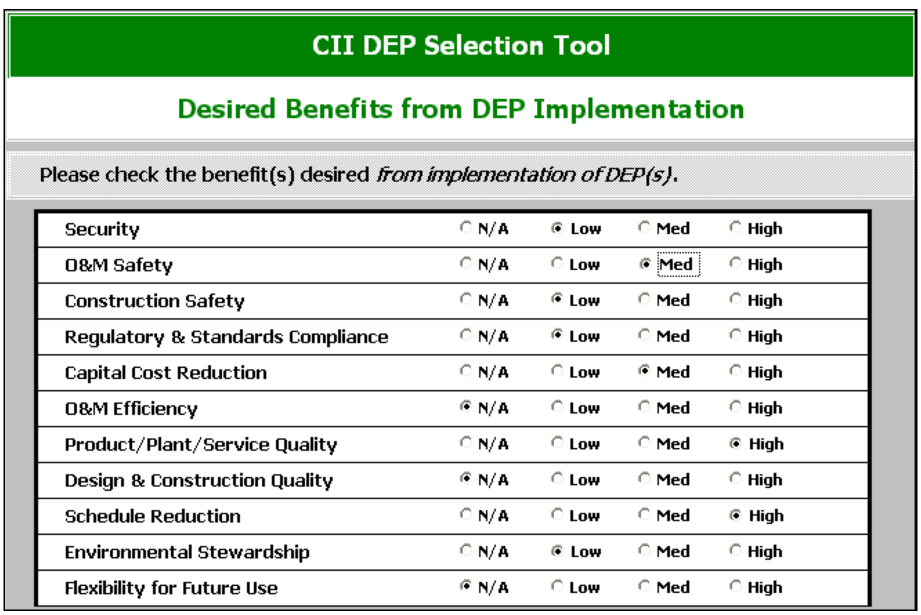


Figure 5.7: Relative Priority of Project Value Objectives

Based on the DEP prescreening, the Selection Tool screens a listing of 94 project characteristics to form a query for characterizing the subject project. With an Agree check box, the user is asked to identify the characteristics of the subject project.

To complete this step, you will need to review 73 statements that characterize your project

Agree	Statement
☐	New contract/delivery process or new technology, or recent major industry event prompts the need for a new or modified design process
☐	Design team has limited experience with related technologies
☐	The project is for a large organization with multiple similar facilities, or is a common project type within an industry sector
☐	Large organization with broad EPC or turn-key like breadth of scope
☐	Company culture is receptive to experience sharing
☐	Project involves many first-time participants
☐	Project team is large and complex
☐	Best or most economical technical resources (i.e. specialists) are geographically separated
☐	Owner/client can be a target of violent subversive groups

Figure 5.8: Sample of Project Characteristics for Describing Project

5.5.3 Structure of Results

The DEP Selection Tool rank orders the recommended DEPs for implementation. Individual scores for Timing, Project Characteristics, Desired Benefits, and Composite scores are provided for each recommended DEP (Figure 5.9). The list can be resorted according to any of the component scores. The recommended DEPs and their scores can also be mapped out in chart form (Figure 5.10).

Rank	DEP Title	Timing Score Interpretation (A)	Project Characteristics Score Interpretation (B)	Desired Benefits Score Interpretation (C)	Composite Score Interpretation (=Ax(0.4B+0.6C))
1	Change Management	10	0.83	0.61	7.0
2	Design to Capacity	10	0.80	0.58	6.7
3	Value Engineering in Design	10	0.80	0.58	6.7
4	3D & 4D CAD	10	1.00	0.38	6.3
5	Standard Design Delivery Process	10	1.00	0.37	6.2
6	Design Automation & Software	10	1.00	0.33	6.0
7	Design Quality Management /QA/QC	10	0.89	0.40	6.0
8	Vendor Integration & Design for Supply Chain	10	0.95	0.33	5.8
9	Design for Startup	10	0.89	0.37	5.8
10	Technology Tracking & Selection	10	1.00	0.29	5.8
11	Design Productivity Tracking	10	0.77	0.42	5.6

Figure 5.9: DEP Ranking and Scores Results

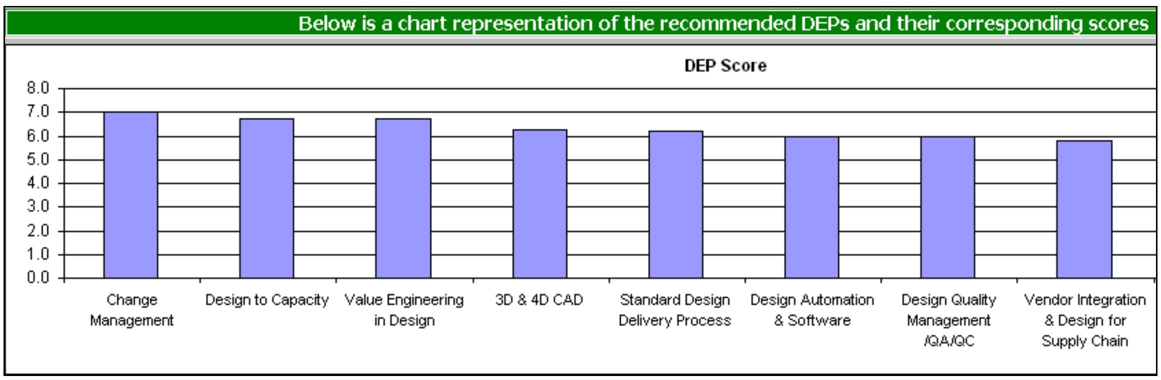


Figure 5.10: DEP Scores Presented in Chart Form

The tool also allows the user to view three Project Characteristics that helped drive the selection of each DEP (Figure 5.11).

Rank	DEP Title	Top 3 Project Characteristics
1	Change Management	• Project team is large and complex • Project definition is ineffectively established or likely to change • Previous similar projects have suffered from substantial scope creep
2	Design to Capacity	• Owner is committed to life-cycle cost reduction analysis • Existing plant may contain "hidden" capacity • Plant capacity and system capacity objectives are not well understood or agreed upon

Figure 5.11: Project Characteristics as DEP Selection Drivers

5.6 *Interpreting Tool Recommendations*

As shown in Figure 5.9, the Timing Score is on a 0 to 10 point scale. This score represents the potential benefit from DEP implementation relative to the current timing of the project (or available timing for DEP implementation). A score of 8 or higher is very good.

The Project Characteristics Score is on a 0.20 to 1.00 scale. This score represents the suitability of the DEP as responsive to the previously established project characteristics. A score of 0.5 to 0.7 is good; a score over 0.7 is very good.

The Desired Benefits Score is on a -0.25 to 1.0 scale, this score represents the relative magnitude of benefit of a DEP according to all targeted Project Value Objectives. A negative score indicates an unsuitable application for the desired benefits chosen. A score of 0.5 to 0.7 is good; a higher score is very good. The scores are affected by the degree of benefit sought (i.e., relative priority: Low, Med, or High).

Finally, the Composite Score is on a 0.00 to 10.00 scale. A weighted average of the Project Characteristics and Desired Benefits Scores is multiplied by the Timing score to determine the Composite Score. The Composite score should be interpreted as follows:

- > 7: DEP is Highly Recommended for implementation;
- 5 to 7: DEP is Recommended for implementation;
- 3 to 5: DEP May be Recommended for implementation but additional team analysis and discussion is needed;
- <3: DEP is Not Recommended for implementation.

Chapter 6: DEP Selection Tool Validation

As mentioned in the Methodology, the analysis of responses was divided into two steps. The first involved comparing the rankings matching between the Structured Manual approach and the DEP Selection Tool. The second step of the analysis used the phone interview to determine whether the tool recommended rankings meet the user needs and expectations. 12 projects were originally used in the survey, but only those that completed the entire process were included in the validation analysis. With six projects completely responding, the overall response rate for the survey was 50%. Table 6.1 lists information on projects used in the validation.

Table 6.1: Information on projects participating in the validation exercise

Project	Type	Location	Project Size	Participant Role
A	Semi Conductor Manufacturing Facility	Chandler, Arizona	> $500MM	Owner: Design Manager
B	Power Plant	Sao Paolo, Brazil	208 MW*	Contractor: Energy System Engineer
C	Water Treatment Plant	Coral Springs, Florida	8 MGD*	Contractor: Design Manager
D	Building Expansion	Hillsboro, Oregon	$11.2MM	Contractor: Design Manager
E	Interior Renovation	Washington, DC	18,000 sq ft*	Owner: Design Manager
F	Mechanical Systems Renovation	Washington, DC	$850K	Owner: Design Manager

*** Project Cost undisclosed; design not finalized at time of inquiry**

6.1 *Structured Manual vs. Automated Tool Analysis*

First step of analysis compared the rate of matching and consistency between the DEP rankings of the Structured Manual approach and the recommended DEP Selection Tool. The criteria used were defined as:

- Top 10 match (Manual-to-Tool): The proportion of the top 10 DEPs from the Structured Manual approach that were also ranked among the top 10 DEPs recommended by the Tool.
- 4-ranks' consistency (Manual-to-Tool): The proportion of the matched DEPs with a difference of 4 or less ranks between them.

Figure 6.1 through Figure 6.6 show the layout of the matching responses between the "Intuitive", "Structured Manual", and "Selection Tool" responses. The difference in responses between the "Intuitive" and "Structured Manual" processes was minimal, and in come cases the responses were identical. A possible explanation for this is that the respondents' decisions were still being influenced by the "intuitive" process responses, limiting their analysis of the other possible factors in determining the rankings of DEPs.

Project A

RANK	Intuitive DEP #	Intuitive Title	Manual DEP #	Manual Title	Tool DEP #	Tool Title
1	5	Change Management	5	Change Management	13	Design for Construction Safety
2	2	Design Quality Management /QA/QC	2	Design Quality Management /QA/QC	11	Design for Constructability
3	13	Design for Construction Safety	13	Design for Construction Safety	8	Design Automation & Software
4	11	Design for Constructability	11	Design for Constructability	5	Change Management
5	17	Design for Maintainability	17	Design for Maintainability	4	Lessons-Learned System/Learning C
6	22	Design for Reliability	22	Design for Reliability	29	Value Engineering in Design
7	29	Value Engineering in Design	29	Value Engineering in Design	2	Design Quality Management /QA/QC
8	26	Design for Sustainability	26	Design for Sustainability	21	Design for PPMOF
9	27	Design to Capacity	27	Design to Capacity	30	Vendor Integration & Design for Sup
10	23	Design for Schedule Performance	23	Design for Schedule Performance	6	Design Productivity Tracking

Figure 6.1: Matching responses for Project A

Project B

RANK	Intuitive DEP #	Intuitive Title	Manual DEP #	Manual Title	Tool DEP #	Tool Title
1	14	Design to Cost	19	Design for Operational Safety	19	Design for Operational Safety
2	19	Design for Operational Safety	18	Design for Operational Automation	25	Design for Startup
3	16	Design for Expandability	3	Design Standardization/PIP	2	Design Quality Management /QA/QC
4	2	Design Quality Management /QA/QC	14	Design to Cost	3	Design Standardization/PIP
5	3	Design Standardization/PIP	10	Technology Tracking & Selection	23	Design for Schedule Performance
6	23	Design for Schedule Performance	16	Design for Expandability	27	Design to Capacity
7	25	Design for Startup	2	Design Quality Management /QA/QC	10	Technology Tracking & Selection
8	27	Design to Capacity	23	Design for Schedule Performance	18	Design for Operational Automation
9	18	Design for Operational Automation	25	Design for Startup	16	Design for Expandability
10	10	Technology Tracking & Selection	27	Design to Capacity	14	Design to Cost

Figure 6.2: Matching responses for Project B

Project C

RANK	Intuitive DEP #	Intuitive Title	Manual DEP #	Manual Title	Tool DEP #	Tool Title
1	22	Design for Reliability	17	Design for Maintainability	11	Design for Constructability
2	26	Design for Sustainability	22	Design for Reliability	6	Design Productivity Tracking
3	27	Design to Capacity	26	Design for Sustainability	27	Design to Capacity
4	3	Design Standardization/PIP	27	Design to Capacity	4	Lessons-Learned System/Learning C
5	11	Design for Constructability	11	Design for Constructability	5	Change Management
6	1	Standard Design Delivery Process	1	Standard Design Delivery Process	1	Standard Design Delivery Process
7	7	3D & 4D CAD	2	Design Quality Management /QA/QC	2	Design Quality Management /QA/QC
8	17	Design for Maintainability	3	Design Standardization/PIP	8	Design Automation & Software
9	20	Design for People	20	Design for People	29	Value Engineering in Design
10	23	Design for Schedule Performance	29	Value Engineering in Design	23	Design for Schedule Performance

Figure 6.3: Matching responses for Project C

Project D

RANK	Intuitive DEP #	Intuitive Title	Manual DEP #	Manual Title	Tool DEP #	Tool Title
1	11	Design for Constructability	11	Design for Constructability	11	Design for Constructability
2	2	Design Quality Management /QA/QC	2	Design Quality Management /QA/QC	21	Design for PPMOF
3	5	Change Management	5	Change Management	13	Design for Construction Safety
4	16	Design for Expandability	16	Design for Expandability	27	Design to Capacity
5	13	Design for Construction Safety	13	Design for Construction Safety	29	Value Engineering in Design
6	26	Design for Sustainability	26	Design for Sustainability	19	Design for Operational Safety
7	17	Design for Maintainability	17	Design for Maintainability	22	Design for Reliability
8	23	Design for Schedule Performance	23	Design for Schedule Performance	5	Change Management
9	6	Design Productivity Tracking	6	Design Productivity Tracking	10	Technology Tracking & Selection
10	22	Design for Reliability	22	Design for Reliability	2	Design Quality Management /QA/QC

Figure 6.4: Matching responses for Project D

Project E

RANK	Intuitive DEP #	Intuitive Title	Manual DEP #	Manual Title	Tool DEP #	Tool Title
1	20	Design for People	20	Design for People	17	Design for Maintainability
2	14	Design to Cost	19	Design for Operational Safety	15	Design for Energy Efficiency
3	24	Design for Security	14	Design to Cost	11	Design for Constructability
4	26	Design for Sustainability	24	Design for Security	2	Design Quality Management /QA/QC
5	23	Design for Schedule Performance	26	Design for Sustainability	26	Design for Sustainability
6	11	Design for Constructability	15	Design for Energy Efficiency	23	Design for Schedule Performance
7	15	Design for Energy Efficiency	17	Design for Maintainability	19	Design for Operational Safety
8	17	Design for Maintainability	11	Design for Constructability	1	Standard Design Delivery Process
9	22	Design for Reliability	2	Design Quality Management /QA/QC	22	Design for Reliability
10	19	Design for Operational Safety	1	Standard Design Delivery Process	20	Design for People

Figure 6.5: Matching responses for Project E

Project F

RANK	Intuitive DEP #	Intuitive Title	Manual DEP #	Manual Title	Tool DEP #	Tool Title
1	15	Design for Energy Efficiency	15	Design for Energy Efficiency	27	Design to Capacity
2	20	Design for People	17	Design for Maintainability	28	Risk-Based Design
3	22	Design for Reliability	19	Design for Operational Safety	11	Design for Constructability
4	17	Design for Maintainability	11	Design for Constructability	21	Design for PPMOF
5	18	Design for Operational Automation	18	Design for Operational Automation	13	Design for Construction Safety
6	14	Design to Cost	1	Standard Design Delivery Process	8	Design Automation & Software
7	19	Design for Operational Safety	21	Design for PPMOF	25	Design for Startup
8	11	Design for Constructability	20	Design for People	15	Design for Energy Efficiency
9	13	Design for Construction Safety	22	Design for Reliability	17	Design for Maintainability
10	8	Design Automation & Software	13	Design for Construction Safety	26	Design for Sustainability

Figure 6.6: Matching responses for Project F

Table 6.2 lists the match rate between the “Structured Manual” and “Selection Tool” processes for the six projects according to the criteria mentioned earlier. The average Top-10 match rate was 63%, while the average 4-ranks consistency percent was 48%. Although this does not indicate a strong consistency between the responses (it does not meet the thresholds established for the criteria), it does not invalidate either of the rankings methods. The rankings must be evaluated in detail before determining the appropriate ranking. Only by asking the participants in detail about their preferred rankings between the two can one identify the most suitable DEP ranking. That is where the third phase of the validation process, the phone interview, comes into play.

Table 6.2: Consistency Analysis Results

Project	Top 10 match (Manual-to-Tool)	4-ranks consistency % (Manual-to-tool)
A	50%	60%
B*	100%	30%
C	50%	80%
D	50%	60%
E	80%	38%
F	50%	20%
Avg	**63%**	**48%**
Threshold	**80%**	**60%**

***Project B did not participate in the Phone Interview portion of the validation**

6.2 *Phone Interview Analysis*

The second step of the validation analysis involved using the ranking assessments inquired in the phone interviews to identify the reliability of the DEP Selection Tool rankings. Five of the six participants were available for the phone interview. The interview consisted of six questions, with questions 3 and 4 focusing on the assessment of the rankings. A sample survey is provided in Appendix G.

The first question asked in the phone interview was “Did you find the Automated Selection Tool helpful in selecting the DEPs?” The options for response were “Yes” and “No (please explain in question 3)”. The second question was “How confident were you in assessing the Project Characteristics?” The options available were “Mostly Confident”, “Somewhat Confident”, and “Not Very Confident”.

The participants were asked in question 3 to assess the ranking of the DEPs recommended by the Selection Tool. The participants were asked to identify the appropriateness of each of the 10 DEPs ranked by the tool based on the following options:

a) The two ranks are very similar (within 2 ranks’ difference)
b) This DEP was deliberately excluded from the analysis
c) I am not familiar with this DEP
d) Recommended DEP is not appropriate because…
e) Recommended DEP is appropriately ranked
f) Recommended DEP is appropriate for the project, but with a different rank

The participants were also asked to clarify the reasoning behind their choice of one of the five options. This exercise was primarily meant to criticize the DEP rankings without influence from the Structured Manual responses. As such, the participants would be judging the rankings list for what it was, rather than comparing it to another. The detailed assessment process guides the participants through a structured analytical process that asks for explanations for their choices.

Question 4 of the phone interview asked the participants to assess their selection of the DEPs in the Structured Manual approach. This section of the interview reviewed each of the top 10 ranked DEPs by the participants in the first survey of the validation. The participants were asked to assess each of their DEPs as:

a) DEP already addressed in Part 3
b) DEP should remain a high priority because…
c) DEP is appropriate for project, but should not be in the top 10
d) DEP should not have been selected for this project.

The purpose of this exercise was to assess the Structured Manual process rankings *after* assessing the DEP Tool rankings in detail. This would help the participant rethink the original rankings provided. Since the "Intuitive" and "Structured Manual" process responses were very similar, this exercise would in essence provide an evaluation for both responses.

Question 5 asked the participant to comment on the Tool by listing any Advantages, Disadvantages, or Suggestions. Question 6 asked what method the participant preferred in selecting DEPs: “The intuitive method”, “The Structured Manual Process”, or “The DEP Selection Tool”.

The participant responses were then tabulated for comparison and analysis. The following main thresholds for evaluation were established based on the ranking assessment options provided in the interview:

- 80% Top-10 Match rate (Tool-to-User), where:

  Top 10 match rate = ([two ranks similar] + [DEP is appropriately ranked] + [DEP is appropriate but with a different rank]) / 10
- 60 % 4-ranks' Consistency rate (Tool-to-User), where:

  4 ranks' consistency rate = ([two ranks similar] + [DEP is appropriately ranked]) / [number of top-10 matching]

The logic behind these thresholds was minimizing the tool errors. Similar research used a threshold of 70% for both criteria. Due to the tight scoring nature of the DEP Selection Tool (e.g.: there is less distinction between some DEP scores in the PVO Objective matrix), the research team opted to increase the match rate but decrease the consistency rate thresholds. Considering that the tool is intended to initiate discussion about DEPs among the design team members rather than provide an absolute list, these thresholds provide a balance between the rigidity of matching expectations and flexibility of including alternatives.

Table 6.3 displays the results for the first two questions in the phone interview (usefulness of the Selection Tool and user confidence in assessing project characteristics). All the participants found the Selection Tool helpful in the selection process. All the participants also claimed to be mostly confident in their assessment of project characteristics. This indicates that the participants knew enough about the projects to assess the DEP applicability on the projects. Both criteria passed their thresholds (80%).

Table 6.3: Results of Questions 1 and 2 in Phone Interview

Project	**1. Was the Selection Tool Helpful?**	**2. Confidence in assessing Project Characteristics**		
		Mostly Confident	Somewhat Confident	Not Very Confident
A	Yes	✓		
C	Yes	✓		
D	Yes	✓		
E	Yes	✓		
F	Yes	✓		
Total	**100%**	**100%**	**0**	**0**
Threshold	**80%**	**80%**		

Table 6.4 displays the results for question 3 (assessing the Selection Tool ranking appropriateness for the project). The table lists the number of total responses for each of the options given for assessment. The two rankings were considered similar if with a difference of two ranks. The results indicate that on average the tool rankings matched the Structured-Manual rankings 2.4 times out of 10. None of the participants replied that

a DEP ranked by the tool had been deliberately excluded in the Structured Manual process, nor did any say they were unfamiliar with any of the DEPs ranked by the Selection Tool. The participants viewed that the Tool had appropriately ranked a DEP (which was different by more than two ranks from the Structured Manual rankings) on an average of 3 out of 10 times. The participants also viewed that on average 3.2 out 10 times the DEPs were appropriate for the project, but with a different rank.

By using the data from Question 3, the research team could compare the results of the rankings versus the thresholds established in the methodology. The criteria calculations produced the following results:

- Top-10 Match rate (Tool-to-User) = (2.4 + 3 + 3.2)/10 = (8.6)/10 = 86%
  (passes threshold of 80%)
- 4-ranks' Consistency rate (Tool-to-User) = (2.4 + 3)/8.6 = (5.4)/8.6 = 63%
  (passes threshold of 60%)

Table 6.4: Results for Question 3 in Phone Interview

Project	**3. Assess DEP Tool Ranking Appropriateness for Project**					
	DEP Excluded	DEP Not Familiar	The two rankings are similar	DEP Appropriately Ranked	DEP Appropriate, but different Rank	DEP not Appropriate
A	0	0	3	4	3	0
C	0	0	4	0	6	0
D	0	0	2	5	1	2
E	0	0	2	3	2	3
F	0	0	1	3	4	2
Avg. out of 10	**0**	**0**	**2.4**	**3**	**3.2**	**1.4**

The results indicated that the validation passes the threshold at this point of the analysis, but they did not specify the major areas of mismatch between the Selection Tool and the users' expectations. As such, the team compiled all the mismatched DEPs for each project. Table 6.5 provides a compilation of the mismatched DEPs and the reasons behind the users' assessing them differently.

Project A was a Semi Conductor Manufacturing Facility. Three of the DEPs ranked by the tool were of a similar rank in the Structured Manual process. Moreover, none of the DEPs ranked by the tool were viewed as inappropriate for the project. Most of the DEPs were appropriately ranked, while three DEPs were appropriate but with a different rank. Due to the nature of the business on this project, Change Management was a very important DEP. Quality Management was also a top priority due to the complexity of design and the multitude of design packages and disciplines involved on the project

Project C was a Water Treatment Facility. Although some DEPs matched the ranking, others (Design for Constructability, Design Productivity Tracking, Lessons-Learned, Change Management, Design Automation, and Design for Schedule Performance) were viewed as having lower ranks due to the company policy of implementing elements of DEPs as a regular part of the process, thus making those DEPs redundant and seem lower in priority.

Project D was a Facility Expansion project. Two DEPs were not appropriate for the project: Design for PPMOF and Value Engineering in Design. The former was not applicable on a project that was mostly in-house, while the latter conflicted with company policies for set parameters. There was also one DEP, Change Management, that should have been a higher priority due to company policy. However, most of the DEPs were appropriately ranked.

Project E was a simple interior renovation project, therefore some of the DEPs simply did not apply due to the limited scope of the project (Design for Maintainability, Design Quality Management, Design for Operational Safety). Design for Energy Efficiency should have been ranked lower, while Design for People should have been ranked higher due to the company business model in needing to prioritize security and schedule.

Project F was also a small-scale project. The MEP installation was already warranted by the manufacturer, and thus one of the DEPs, Risk-Based Design, did not apply. The nature of the installed components also made Design for Sustainability irrelevant. Safety was not as high a priority as Energy Efficiency and Maintainability, as the former was covered by another group while the latter two were the very essence of the project. The discrepancies in rankings were due to the small project size and the timing of implementation of DEPs during mid-design.

Table 6.5: Summary of Reasons for Mismatched DEPs

Project	Mismatched DEPs	Reason for mismatch
A	Change Management	Nature of business
	Quality Management	Complex Design
C	Design for Constructability, Design Productivity Tracking, Lessons-Learned, Change Management, Design Automation, Design for Schedule Perform.	Viewed as having lower ranks due to the company policy of implementing elements of DEPs as a regular part of the process; DEPs seem redundant.
D	Design for PPMOF	**Not Appropriate:** Not Applicable; In-house Project
	Value Engineering in Design	**Not Appropriate:** Conflicts with Company policy
	Change Management	Company Policy
E	Design for Maintainability Design Quality Management Design for Operational Safety	**Not Appropriate:** Limited Scope of Project
	Design for Energy Efficiency Design for People	Company Business Model
F	Risk-Based Design	**Not Appropriate:** Not Applicable; parts already warranted by manufacturer
	Design for Energy Efficiency Design for Maintainability	**Not Appropriate:** Not Applicable; Nature of installed components
	Design for Safety Design Automation	Not as high a priority; cover by another team
	Design for Sustainability	Essence of the project; top priority

Table 6.6 provides a summary of DEPs that were identified as “inappropriate for the project” and those that were “appropriate, but with a different rank”. There appears to be no pattern for DEPs that were “inappropriate”, but Change Management, Design Productivity Tracking, and Design Automation occurred more than once as appropriate DEPs with a different rank. Change management was viewed as being under-ranked on

two counts, and over-ranked on another. Design Productivity Tracking and Design Automation were viewed as over-ranked on two occasions each.

Table 6.6: Summary of Mismatched DEPs in Question 3 (Selection Tool)

Project	**DEP not Appropriate**	**DEP Appropriate, but different Rank** **+ = should be higher** **– = should be lower**
A		Change Management + Design Quality Management + Design Productivity Tracking –
C		Design for Constructability – Design Productivity Tracking – Lessons-Learned – Change Management – Design Automation – Design for Schedule Performance –
D	Design for PPMOF Value Engineering in Design	Change Management +
E	Design for Maintainability Design Quality Management Design for Operational Safety	Design for Energy Efficiency – Design for People +
F	Risk-Based Design Design for Sustainability	Design for Safety – Design for Energy Efficiency + Design for Maintainability + Design Automation –
Mode	**None**	**Change Management (2+, 1–)** **Design Productivity Tracking (2–)** **Design Automation (2–)**

Table 6.7 displays the results for question 4 in the interview (assessing the Structured Manual ranking appropriateness for the project). The table lists the number of total responses for each of the options given for assessment. On average, 5.6 out of 10 DEPs were already covered in the Selection Tool rankings, 4 out of 10 were not covered by the tool but should remain high priorities, and 0.4 out of 10 were identified as appropriate but

not top 10 by users. None of the responses identified a DEP as "should not have been selected".

Table 6.7: Results for Question 4 in Phone Interview

Project	**4. Assess Structured Manual Ranking Appropriateness for Project**			
	DEP Addressed in question 3	Non-selected DEP should remain high priority	DEP Appropriate, but not top 10	DEP should not have been selected
A	5	5	0	0
C	5	4	1	0
D	5	4	1	0
E	8	2	0	0
F	5	5	0	0
Total	**5.6**	**4**	**0.4**	**0**

Project A (Semi Conductor Manufacturing Facility) listed Maintainability, Schedule, and Capacity as concerns on the project due to the need for constant manufacturing, meeting complex schedules, and the need to expand facilities. These priorities were among the top ten, but not the top five items on the list.

Project C (Water Treatment Facility) preferred to prioritize certain DEPs that were not covered in the Selection Tool Top 10 due to the scope of the project and the nature of the work process (such as quality taking supremacy over schedule). However, upon assessment of one of the DEPs in the Structured-Manual list, the participant mentioned that it was not a top 10 DEP due to the changing preferences of the client.

Project D (Facility Expansion) had a reasonable match between the Selection Tool and the Structured-Manual Process. One of the DEPs was re-evaluated as not a very high priority due to the company's changing business environment

Project E (Interior Renovation) had a high match between the Selection Tool and the Structured-Manual Process. The two DEPs that did not overlap were still considered a high priority for the project.

Project F (MEP installation) prioritized Operational Safety, Reliability, and Standardization. As such, half of the Structured-Manual process DEPs were listed by the Selection Tool, but those that were not were not ranked high by the tool due to the very specific nature of the project.

Table 6.8 presents a summary of the DEP ranking assessment in Question 4. The two main DEPs that stood out as ones that "should remain a high priority" (and were not covered by the Selection Tool) were Design for Reliability and Design for Sustainability. Both DEPs were identified three times each. However, there was no significant pattern among the DEPs that were identified as "Appropriate but not top-10".

Table 6.8: Summary of Assessment of DEPs in Question 4 (Structured Manual Survey)

Project	**DEP should remain high priority**	**DEP Appropriate, but not top 10**
A	Design for Maintainability Design for Reliability Design for Sustainability Design to Capacity Design for Schedule Performance	
C	Design for Reliability Design for Sustainability Design Standardization Design for People	Design for Maintainability
D	Design for Expandability Design for Maintainability Design for Sustainability Design Productivity Tracking	Design for Schedule Performance
E	Design for Cost Design for Security	
F	Design for Operational Safety Design for Operational Automation Standard Design Delivery Process Design for People Design for Reliability	
Mode	**Design for Reliability (3)** **Design for Sustainability (3)**	**None**

Question 5 asked the participants to provide feedback on the DEP Selection tool. The responses provided were as follows:

Advantages:

- Intuitive interface
- Helps discussion during kick-off meeting
- Smooth and straight-forward
- Structured methodology

- Displays concepts
- Helps reveal DEPs that might have been overlooked
- Allows users to set relative priorities
- Applicable to a flexible variety of projects
- Overall project match makes sense
- Helps one think about the project characteristics

User Perceived Disadvantages:

- One participant's company has its own specialize, in-house DEP Selection Tool
- Unfamiliarity with the tool and lack of training might be a bit intimidating
- Design team might grow dependent on the tool and lose the drive of thought process to laziness
- Mainly geared to medium to big size projects
- Does not capture the needs of very small and specific projects

User Suggestions:

- Customize some terms for different companies that might have different terminology
- Adapt to small size projects
- Refine the process to adapt to mid-design phase projects (however, the benefits of DEP implementation drastically diminish at this phase)

Question 6 asked the users about their preference for methods of DEP selection. Table 6.9 shows the answers given. The responses were unanimously in favor of the Selection Tool. It indicates that the tool passes the criteria threshold for "Tool Preference" (80%).

Table 6.9: Results for Question 6 in Phone Interview

Project	**6. Which approach do you prefer?**		
	Intuition Based	Structured Manual	Automated Tool
A			✓
C			✓
D			✓
E			✓
F			✓
Total	**0**	**0**	**100%**
Threshold			**80%**

6.3 *Recommended Adjustments to Tool*

The DEPs that stood out as in need of adjustment were: Change Management, Design Productivity Tracking, Design Automation, Design for Reliability, and Design for Sustainability. The first three were appropriately recommended by the tool, but the users felt that the rank should be different, while the last three were DEPs that the Tool did not list among the top 10 although the users felt that they should be a high priority.

Change Management had 8 Project characteristics (DEPs on average have 5 project characteristics) and the users felt that it was ranked by the tool too low on two accounts and too high on another. The Characteristics Score was lower than other similar DEPs because users were not identifying enough characteristics. However, due to being ranked as too high and too low, more data would be needed to determine whether this is due to user input or a flaw in the characteristics matrix. As such, no adjustments were recommended.

Design Productivity Tracking had 4 Project characteristics and was assessed as being ranked too high twice. The Characteristics Score was high in one case, although DEP does not share many characteristics with other DEPs (i.e.: this is a user input issue). The recommendation for this DEP was the adjust of the timing score (out of 10) from 10, 6,0 to 10,4,0 (for 0%,25%,65% design complete respectively).

Design Automation had 7 Project characteristics, but its Characteristics Score was not an issue. It was Ranked too high twice. Similar to Design Productivity Tracking, the recommendation for this DEP was the adjust timing score (out of 10) from 10, 6,0 to 10,4,0 (for 0%,25%,65% design complete respectively). The reason behind this adjustment for these two DEPs was that Design Productivity tracking & Design Automation were the only two DEPs with a 10,6,0 timing gradient. All others are 10,6,2 or 10,4,0. The exception to this was “Technology Tracking & Selection”, which also had a 10,6,0 gradient, but did not appear as a problematic DEP.

Of the DEPs viewed as high priority but not listed by the Tool, Design for Reliability and Design for Sustainability ranked between 11 and 15 on the Tool recommendations.

Therefore only a minor adjustment was needed to push them up among the top 10.

Design for Reliability had 3 characteristics, but Characteristics score was not an issue (it was high is all cases). The reason for this DEP's low rankings was that users ranked O&M lower than other PVO, or completely excluded the PVO from the analysis. Since users need to realize that O&M is an essential component of Reliability, no adjustment needed for this DEP.

Design for Sustainability had 7 characteristics, and again Characteristics Score was not an issue. Users tended to view Sustainability was related to Quality. The recommended Adjustment for this DEP is in the PVO table: the score for "Product/Plant/Service Quality" should be changed from + to ++.

The adjustments were tested using the same inputs provided by participants in their Selection Tool submissions. The new rankings were compared to the old ones and the average rank gained / lost was recorded. Table 6.10 presents a Summary of the problematic DEPs, their solutions, and the rank gain / loss after implementation of adjustments. The suggested adjustments were presented to the RT233 expert panel and two of the three recommendations were approved (editing the Timing score for Design Productivity Tracking and Design Automation)

Table 6.10: Summary and Results of Recommended Adjustments

DEP	*Mismatch Reason*	*Problem*	*Recommended Adjustment*	*Rank Gain (Avg)*	*Approved by Expert Panel*
Change Management	Appropriate, but should be higher (2) or lower (1)	Users do not identify characteristics	none	N/A	
Design Productivity Tracking	Appropriate, but should be lower	Timing score gradient different	Edit Timing Score Matrix Score from 10, 6,0 to 10,4,0	-2.7	Yes
Design Automation	Appropriate, but should be lower	Timing score gradient different	Edit Timing Score Matrix Score from 10, 6,0 to 10,4,0	-2.6	Yes
Design for Reliability	Does not appear in Top 10	Users do not prioritize O&M	none	N/A	
Design for Sustainability	Does not appear in Top 10	PVO Score is low	Edit PVO Score Matrix Score. Change "Product/Plant/Service Quality" from + to ++	+5.3	No

Table 6.11: Updated Tool Ranking Assessments after Implementing Adjustments

Project	**3. Assess DEP Tool Ranking Appropriateness for Project**					
	DEP Excluded	DEP Not Familiar	The two rankings are similar	DEP Appropriately Ranked	DEP Appropriate, but different Rank	DEP not Appropriate
A	0	0	3	5	2	0
C	0	0	4	2	4	0
D	0	0	2	5	1	2
E	0	0	2	3	2	3
F	0	0	1	4	3	2
Avg. out of 10	**0**	**0**	**2.4**	**3.8**	**2.4**	**1.4**

The new ranks created by the adjustments were also used to recalculate the values in the DEP Tool Rankings Assessment table (Table 6.4). The adjustments did not shed any of the DEPs that were labeled as "not appropriate", nor was there a gain in the "Two Rankings are Similar section" (See Table 6.11). However, there was a noticeable shift from DEPs that were labeled as "Appropriate, but with a different rank" to "Appropriately ranked". "Appropriately Ranked" DEPs rose on average by 0.8 (from 3 to 3.8 out of 10), while "Appropriate but with a different rank" DEPs dropped by 0.8 (from 3.2 to 2.4). The new Match rate and Consistency rates were recalculated to be:

- Top-10 Match rate (Tool-to-User) = (2.4 + 3.8 + 2.4)/10 = (8.6)/10 = 86%
  (passes threshold of 80%)
- 4-ranks' Consistency rate (Tool-to-User) = (2.4 + 3.8)/8.6 = (6.2)/8.6 = 72%
  (passes threshold of 60%)

Although the Top-10 Match rate (Tool-to-User) did not change, the 4-ranks' Consistency rate (Tool-to-User) gained 9% (from 63% to 72%). Both criteria had met their thresholds, but the adjustments show value by boosting the consistency rate.

6.4 *Summary of Validation Analysis*

The manual survey showed a reasonable match between the rankings of the Selection Tool and the Structured Manual Process. There was a 63% top-10 match rate, and a 48% match rate within 4-ranks' difference. Upon further investigation, the phone interview provided some interesting insight into the reasons behind the differences. The most notable factor was that the Selection Tool listed DEPs that had previously eluded the attention of the participants. Almost all the participants mentioned that they appreciated the added perspective the tool provides for discussion among the design team. It is also worthwhile to note that Tool's filtering algorithm do not re-include DEPs that were previously marked for exclusion by the user.

The phone interview results show that all the participants were very familiar with their project characteristics and needs, and their assessment of the two rankings is not without basis. On average, only 1.4 out of 10 (14%) of the DEPs listed by the tool were viewed as inappropriate for their projects, and only 3.2 out of 10 (32%) of the DEPs were identified as "Appropriate but with a different rank". Using the criteria previously established in the methodology, the Top-10 Match rate was recalculated to be 86%, and the 4-ranks' Consistency rate was 63%. These results were above the thresholds established for validation (80% and 60% respectively), and indicate that the users were generally open and receptive to alternative DEP rankings. The participants unanimously agreed that the Selection tool was their preferred method of producing a discussion list of DEPs for implementation on a project. The tool scored 100% for the Usefulness, User familiarity, and Tool Preference criteria, surpassing the established threshold of 80%.

Upon further analysis of the assessment of the DEP Selection Tool rankings, here appears to be no pattern for DEPs that were viewed “inappropriate”, but Change Management, Design Productivity Tracking, and Design Automation occurred more than once as appropriate DEPs with a different rank. Change management was viewed as being under-ranked on two counts, and over-ranked on another. Design Productivity Tracking and Design Automation were viewed as over-ranked on two occasions each. In regards to the assessment of the Structured Manual rankings, the two main DEPs that stood out as ones that “should remain a high priority” (and were not covered by the Selection Tool) were Design for Reliability and Design for Sustainability. Both DEPs were identified three times each.

The recommended adjustments for the problematic mismatched DEPs were to adjust the Timing Score Matrix Scores for Design Productivity Tracking and Design Automation, and adjust the PVO Score Matrix Design for Sustainability. Change Management and Design for Reliability did not have any recommended adjustments. The adjustments were implemented into the DEP Tool and the resulting new rankings were recorded. Design Productivity Tracking and Design Automation lost 2.7 and 2.6 ranks on average, respectively. Design for Sustainability gained 5.3 ranks on average. The RT 233 expert panel approved the adjustments for Design Productivity Tracking and Design Automation, but rejected the alterations for Design for sustainability. These changes were compared in the Assessment of DEP Selection Tool Rankings, and produced a gain of 9% (from 63% to 72%) in 4-ranks' consistency rate (Tool-to-User), while Top-10 Match rate (Tool-to-User) remained unchanged at 86%.

The Selection Tool's main purpose is to initiate discussion, not provide an actual list for application. The participants valued the idea of a tool that does not go against experience, but supplements it. A major perceived disadvantage of the tool was its inability to reflect the specific needs of small / specialized projects. However, the Selection Tool's intuitive interface, structured methodology, customizable priorities, and discussion-enabling advantages add great benefit to its application. One of the suggestions provided was adapting the tool to small-size projects.

Chapter 7: Design Effectiveness Evaluation Tool

7.1 *DE Evaluation Tool Purpose and Benefits*

The automated DE Evaluation Tool was created in order to assist in the evaluation of design effectiveness in the context of capital facility projects. The purpose of this evaluation tool is to provide guidance in assessing how well a project is meeting desired objectives and criteria for design effectiveness. With appropriate user-defined input, the tool computes a DE performance score based on the following project inputs:

- Timing of DE evaluation;
- Relative importance of 11 different Project Value Objectives (PVO);
- Selected or screened sub-criteria associated with each PVO;
- Assessments of individual sub-criteria; and
- Significance weightings of evaluation sub-criteria associated with targeted PVOs.

Readers are referred to Appendix I of this dissertation for the *Design Effectiveness Evaluation Tool User Manual.*

7.2 *DE Evaluation Tool Logic*

The tool uses DE evaluation timing and Project Value Objectives to filter out inapplicable (or unintended) sub-criteria. The user is then asked to evaluate the applicable sub-criteria and is also given the option to include / exclude sub-criteria and to adjust sub-criteria weights, if desired. Once the user has entered sub-criteria assessments, the program calculates a score for each of the 11 Project Value Objectives by summing the products of PVO sub-criteria and their corresponding sub-criteria weights. The Composite Score is derived similarly by summing individual PVO weighted scores.

7.3 *DE Evaluation Tool User Interfaces*

7.3.1 High level of customization

The tool provides for screening of individual sub-criteria assessments based on both the Timing of DE Evaluation as selected by the user (Figure 7.1) and the selection / prioritization of Project Value Objectives as indicated by the user (Figure 7.2). On this later tool screen the user assigns the relative importance or significance of each PVO to the project. On this screen the user can also customize PVO weightings. The user also indicates the relative importance of each sub-criterion, as shown in Figure 7.3.

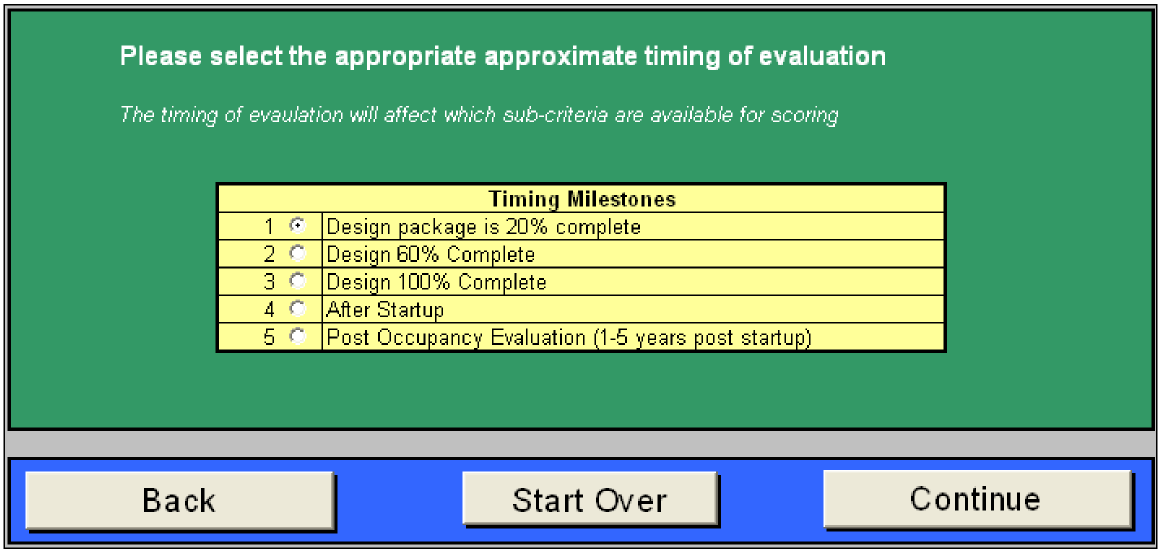
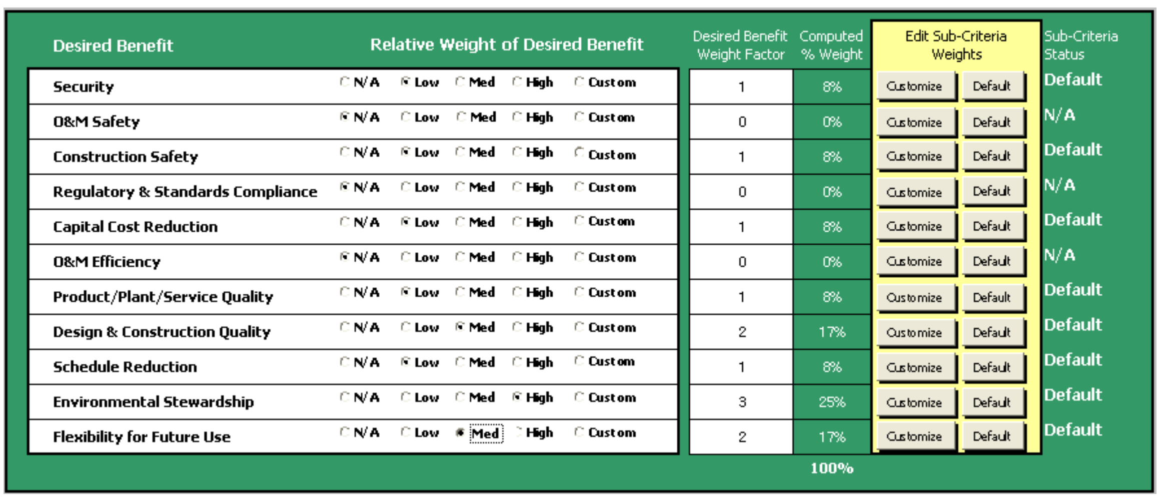


Figure 7.1: Options for Timing of DE Evaluation



Desired Benefit	Relative Weight of Desired Benefit (N/A, Low, Med, High, Custom)	Desired Benefit Weight Factor	Computed % Weight	Edit Sub-Criteria Weights	Sub-Criteria Status
Security	Low	1	8%	Customize / Default	Default
O&M Safety	N/A	0	0%	Customize / Default	N/A
Construction Safety	Low	1	8%	Customize / Default	Default
Regulatory & Standards Compliance	N/A	0	0%	Customize / Default	N/A
Capital Cost Reduction	Low	1	8%	Customize / Default	Default
O&M Efficiency	N/A	0	0%	Customize / Default	N/A
Product/Plant/Service Quality	Low	1	8%	Customize / Default	Default
Design & Construction Quality	Med	2	17%	Customize / Default	Default
Schedule Reduction	Low	1	8%	Customize / Default	Default
Environmental Stewardship	High	3	25%	Customize / Default	Default
Flexibility for Future Use	Med	2	17%	Customize / Default	Default
			100%		

Figure 7.2: Selection/Weighting of Project Value Objectives

7.3.2 Sub-criteria Assessment

The automated DE Evaluation Tool provides the user with up to 105 sub-criteria to consider, with the option of excluding those that the do not apply (Figure 7.4). The tool also allows for the addition of two customizable sub-criteria for each PVO. A link to the interdependency table (See Appendix J) is provided at the bottom of the page.

Back			Subcriteria Weight Factor	Computed % Weight	
1 **Security**	1.1	Facility detects and responds to physical breaches as required	1	0%	**Sub-criteria does not apply**
	1.2	Security of facility information systems is addressed	1	33%	
	1.3	Design Plans & Specifications appropriately address construction security requirements	1	33%	
	1.4	Design Plans & Specifications appropriately address access to hazardous/controlled substances, as required	1	0%	**Sub-criteria does not apply**
	1.5	Security of design information and IP is addressed	1	33%	
	1.6	<CUSTOM>	1	0%	**Sub-criteria does not apply**
	1.7	<CUSTOM>	1	0%	**Sub-criteria does not apply**
				100%	

Figure 7.3: Weighting of Sub-criteria

	1	**Security**
	1.1	**Facility detects and responds to physical breaches as required**
Sub-criteria does not apply ☑		NEVER … OCCASIONALLY … USUALLY … ALWAYS 0 1 2 3 4 5 6 7 8 9 10
	1.2	**Security of facility information systems is addressed**
Sub-criteria does not apply ☐		DO NOT … OCCASIONALLY … USUALLY … TRUE 0 1 2 3 4 5 6 7 8 9 10
	1.3	**Design Plans & Specifications appropriately address construction security requirements**
Sub-criteria does not apply ☐		DO NOT … OCCASIONALLY … USUALLY … DO 0 1 2 3 4 5 6 7 8 9 10
	1.4	**Design Plans & Specifications appropriately address access to hazardous/controlled substances, as required**
Sub-criteria does not apply ☑		DO NOT … OCCASIONALLY … USUALLY … DO 0 1 2 3 4 5 6 7 8 9 10
	1.5	**Security of design information and IP is addressed**
Sub-criteria does not apply ☐		DO NOT … OCCASIONALLY … USUALLY … DO 0 1 2 3 4 5 6 7 8 9 10
	1.6	**<CUSTOM>**
Sub-criteria does not apply ☑		0 1 2 3 4 5 6 7 8 9 10
	1.7	**<CUSTOM>**
Sub-criteria does not apply ☑		0 1 2 3 4 5 6 7 8 9 10

Figure 7.4: Sub-criteria for Security Project Value Objective

7.3.3 Evaluation Results

As shown in Figure 7.5, the tool provides the results of the evaluation in a simple output table, with the option of sorting results information by PVO weights, scores, or weighted scores.

Rank by: Weighted Score	Practive Value Objective	Weight Sort	Score Sort	Weighted Score Sort
1	Environmental Stewardship	25.0%	5.0	1.25
2	Design & Construction Quality	16.7%	5.0	0.83
3	Flexibility for Future Use	16.7%	5.0	0.83
4	Security	8.3%	5.0	0.42
5	Construction Safety	8.3%	5.0	0.42
6	Capital Cost Reduction	8.3%	5.0	0.42
7	Product/Plant/Service Quality	8.3%	5.0	0.42
8	Schedule Reduction	8.3%	5.0	0.42
9	O&M Safety	0.0%	N/A	0.00
10	Regulatory & Standards Compliance	0.0%	N/A	0.00
11	O&M Efficiency	0.0%	N/A	0.00
			Composite Score	5.0

Figure 7.5: DE Evaluation Results Screen

7.4 *Interpreting Tool Results*

The weighted scores are derived by multiplying the PVO Scores by their weights. The Composite Score is then derived as the sum of all the PVO weighted scores. While users may apply their own interpretation to the 10-point scale scores, a score greater than 7 generally indicates a good assessment (shown in green), a score between 3 and 7 indicates an adequate or mixed assessment (shown in yellow), and a score less than 3 indicates a poor assessment (red).

Chapter 8: Conclusion and Recommendations

8.1 *Conclusions*

Effective Design can help in maximizing project value. This research set out to provide a Model for implementing Design Effectiveness for projects of varying size and scope across all industry sectors, as well as to provide tools to aid in the prioritization of Design Effectiveness Practices and the evaluation of Design Effectiveness. In accomplishing this research, this Toolkit is a major advancement on the existing CII Best Practice of Design Effectiveness. Key developments and conclusions from this study include the following:

- Too often, design is not as effective as needed and maximum project value is not achieved. Direction and guidance are needed to achieve targeted value. The implementation model and tools are driven by Project Value Objectives.

- Design Effectiveness is the degree to which the design effort achieves Project Value Objectives.

- Due to the limitations of the CII benchmarking database, little data could be analyzed for the study of the effect of design on project performance metrics. However, the most notable finding in that portion of the analysis of Contractor

Data was that a higher "% of PPP and Design" resulted with a lower Budget Factor, indicating that a greater investment in design tends to lead to a lower project cost.

- Design management fits within the framework of Project Management and the Project Management pursuits of front-end planning, team leadership, stakeholder alignment, and risk management influence Design Effectiveness.

- Design Effectiveness lies at the core of successful Design Management. A listing of key Design Quality/Productivity Drivers has been identified and these should be viewed as essential to effective Design Management.

- The Design Effectiveness Implementation Model presented in this dissertation provides process guidance to owners and designers. Planning for Design Effectiveness Project Implementation is perhaps the most significant step in the Model.

- Thirty diverse Design Effectiveness Practices have been identified through rigorous analysis, and these supplement Design Management. These DEPs have been correlated with the 11 established CII Project Value Objectives and may be applied to projects of various industry sectors, markets, types, and sizes. However, the expert panel that provided these relationships lacked representation from the residential construction sector.

- The Design Effectiveness Practices are primarily intended as optimization techniques, but in some circumstances will also serve as design quality “safety nets”.

- Three detailed DEP application case studies have been included in this research to provide additional guidance on benefits achieved and how to implement in a project context.

- The DEP Selection Tool prioritizes the Design Effectiveness Practices based on user inputs pertaining to implementation timing, targeted benefits, and project characteristics.

- The DEP Selection Tool met the validation criteria thresholds, with an 86% Top-10 Match rate, and a 63% 4-ranks’ Consistency rate. The acceptance thresholds were 80% and 60% respectively. The Tool’s filtering algorithm also did not re-include DEPs that had been previously marked for exclusion by the user. Recommended adjustments were submitted for approval by the research team’s expert panel. After testing the said adjustments to the tool the consistency rate increased to 72%, although the match rate remained the same at 86%.

- During the validation process, Change Management tended to be under-ranked by the tool, while Design Productivity Tracking and Design Automation were seen as over-ranked by the tool. Design for Reliability and Design for Sustainability were viewed as important DEPs that the Tool did not list as often as the users would have liked.

- The less control the user chooses to exploit via the Selection Tool, the greater the mismatch between Recommended and Expected DEP rankings. This occurs when users choose to skip the PVO prioritization and the DEP Inclusion / Exclusion Confirmation sections in the tool.

- The DEP Selection Tool validation survey participants valued the tool's intuitive interface, structured methodology, and customizable priorities. They unanimously preferred the tool over the intuitive and structured manual selection processes. They also appreciated the tool for its main function: facilitating discussion among the design team and providing an alternative perspective.

- The methodology for the validation process used for the tool provides a detailed process for comparison of results between two approaches, with the ability to detect individual items with frequent mismatches between results and adjust them.

- The DE Evaluation Tool computes a composite score using sub-criteria that are organized by and support Project Value Objectives, established criteria scales, and allows for user-defined weightings of Project Value Objectives and sub-criteria.

- The author performed the following duties:
    - Benchmarking Data ANOVA Analysis
    - Synthesizing and editing DEP Characterization Catalog
    - Develop, test, validate, and provide application recommendations for the Selection Tool
    - Develop, test, and update the DE Evaluation Tool
    - Analyze the DE sub-criteria for interdependence

- The Lessons Learned form the validation process include the following:
    - The importance of capturing a larger validation sample size to allow for more quantitative statistical analysis in the process
    - Further characterization of participants (years of experience, interface with project, etc.) would be of value to the validation process

8.2 *Research Contributions*

- The results and knowledge generated from the ANOVA analysis, although limited, provide an indication of the benefits of investment in design and pre-project planning on project cost performance. The results of this research could be used to aid further studies on the topic.

- Current industry practitioners generally use intuition in selecting DEPs. The DEP Selection tool provides a structured, formulated method for selecting DEPs based on prioritized objectives and unique project needs. The integrated tool is a primary contribution from this research.

- The use of a structured selection algorithm and score matrices (developed with the aid of industry experts) is the essence of the Selection Tool and is an advancement of knowledge.

- The core knowledge embedded in the DEP Selection and DE Evaluation tools may offer benefit for future related research.

- The DE Evaluation Tool provides a structured list of sub-criteria for assessing a broad range of objectives in design effectiveness on a project. The tool itself should help practitioners evaluate design effectiveness. The methodology behind the tool, including the use of an expert panel and the sub-criteria interdependency analysis, should lay a foundation for subsequent research.

8.3 *Recommendations*

Potential areas for future related studies have been identified for this research, and include the following:

- A more detailed analysis between Design and performance metrics can only be conducted once the CII Benchmarking database is updated with more design-related metric data.

- The DEP Selection Tool should be updated on a periodic basis, to reflect current trends in DEP application.

- The DEP Selection Tool could be enhanced by allowing greater flexibility in the Project characteristics scoring process, as well as assigning weights to each characteristic (As opposed to the current implementation of equal weighting adjusted through a curve).

- Knowledge gained from Design Effectiveness Evaluation in a specific project should be shared at the organizational level for improvement of subsequent projects.

- Project design evaluation performance data should be collected and compared to DEP implementation to further validate the Selection Tool.

- The overlapping domains and effects of DEPs on a project should be investigated. Some DEPs may act as sub-sets, super-sets, or share a major portion of implementation with other DEPs. An investigation into this subject might help identify optimum combinations of DEPs.

Appendix A: Design Effectiveness Practice Application Case Studies

A.1 *Standard Design Delivery Process Application Case Study*

A.1.1 Introduction

This application case study is intended to further illustrate how the Standard Design Delivery Process DEP can be effectively implemented on projects. As with many projects, the Standard Design Delivery Process DEP played a very significant role in ensuring the overall success of this capital project.

A.1.2 Purpose of a Standard Design Delivery Process Model

A standardized design delivery process provides the framework for a consistent yet flexible approach to planning and executing design projects for any market segment. Industries as diverse as transportation, federal government buildings, sea ports, municipal water and wastewater and power generating plants use defined, repeatable design delivery procedures. Models can be developed for traditional design-bid-build deliveries as well as design-build or EPC deliveries. It is readily used for small and large projects.

In addition, a standard design delivery process serves as a reference point for all aspects of project execution. By providing a defined design process, these guidelines allow all project stakeholders and team members to speak a common language regarding design approach, status, and procedures. This understanding facilitates the execution of projects in different locations and even with the involvement of different companies.

While this application case study is focused on the use of a standardized delivery process, many other Design Effectiveness Practices were also employed on this project. These included:

- Design Quality Management/QA/QC
- Change Management
- Integration of Lessons-Learned into Design
- Design Productivity Tracking
- Design Automation & Software
- Virtual Teams
- Technology Tracking & Selection

- Design to Cost
- Design for Maintainability
- Design for Operational Safety
- Design for Reliability
- Design for Startup
- Value Engineering in Design
- Vendor Integration & Design for Supply Chain

A.1.3 The Four Phase Design Delivery Approach Overview

The design delivery approach used on this project consisted of four phases. The genesis of this approach is one developed by the Architectural Institute of America (AIA). The AIA practice, which is common employed in the AE industry, has been modified to meet the needs of process plants.

The following discussion is applicable to a design-bid-build water or wastewater treatment project. The process would be modified for other types of projects as well as an EPC or design-build delivery. The same basic process is also used for building designs by this firm. While the approach is standard, it is flexible enough that it can easily be tailored to the needs of any client and constructed project.

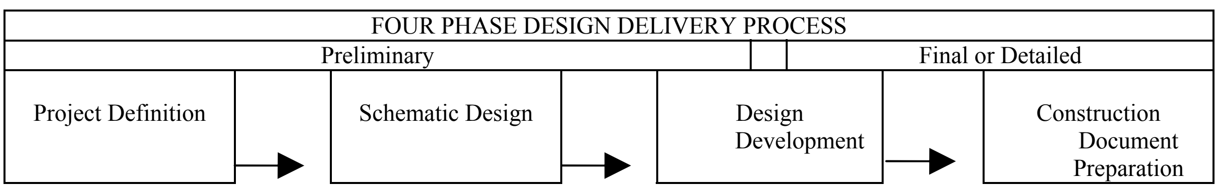


Figure A.1: Four Phase Design Delivery Process

To break down the design process into manageable portions, it is necessary to define distinct design phases, as shown in the exhibit above and described in more detail in a following section.

1. Project Definition
2. Schematic Design
3. Design Development
4. Construction Document Preparation

Note that these phases can easily fit into the preliminary and final design model used by some clients and firms.

This approach facilitates a high degree of client interaction throughout the entire design phase. Client workshops focused on specific issues are held routinely. These tend to be more frequent in the Project Definition and Schematic Design phases when major, far reaching decisions must be made. However, they continue until the client's comments are received on the final review set of design documents. Key client and consultant project team members participate in each session. An atmosphere of collaboration and partnering are key success factors. Of course, that doesn't preclude a few "spirited" discussions from all participants. Indeed, these always add to the value of the final product.

A.1.4 Benefits of this Approach

This approach effectively communicates to both the client and the project team the vision of the final project function and appearance. It also facilitates the execution of designs in different locations and with a diverse team including sub-consultants. The general process — tailored to the needs of individual client and project — results in the following benefits:

- Effective Communications -- As stated above, this approach is a very interactive one. All key stakeholders are involved participants during the life of the design effort and beyond. This leads to nearly continuous and very clear communications which in turn results in alignment of the stakeholders. Unpleasant surprises due to miscommunications are a rare exception when using this approach.

- Work Planning Assistance - Standardized flowcharts, checklists, and project management procedures provide valuable assistance in developing the work plan.

- Management of Change - Using a consistent, universally applied process enables more effective change management — both internal and external. For example, if the client changes the desired facility foot print at the 90-percent design completion stage, a review of the charts with the client can help illustrate the cost and schedule impact of the change. This topic was a standing item on the bi-weekly meetings between the design team manager and the client.

- Consistency - Use of the flowcharts across the entire organization provides consistency among offices, aiding effective movement of project work and the assignment of staff from other offices.

- Efficient delivery – This approach enhances the integration among the various technical disciplines. It prescribes the proper sequencing of the hundreds of activities required to complete a complex design. It serves as the play book for the entire project team.

- Training - The work process flowcharts, with their explanations and checklists, facilitate self-learning and just-in-time training of inexperienced or new staff, including sub-consultant staff. A well documented design deliver model enhances the on-the-job training acquired by working with an experienced project team.

- Management of Quality - By anchoring the design services in a proven delivery process, the design professional advances the quality of their work. Using a continuous quality control model builds in excellence from the start because this model is based on incremental work, followed by approval and endorsement of the work. Decisions made this way are incorporated into the project and serve as the basis for subsequent work. This process avoids wasted effort and the cost of redoing work later in the project.

- Continuous Improvement- By documenting the way things are done—or the way the organization strives to do things—the designer can adjust the processes and approaches as they are tried and as desired modifications are identified. The result is team learning through individual contribution.

- Cost Reduction - Cost effectiveness results from mutually aligning expectations when undertaking work in accordance with proven processes. This process allows the increase of profit margins while still meeting and usually exceeding the expectations of the client. It also facilitates the effective use of value engineering techniques. These can be through a formal value engineering effort or by the design team using those techniques to continually reduce costs.

- Client Satisfaction - Consistently high-quality work, delivered cost effectively and in a reasonable time period, contributes to client satisfaction. A comment that is frequently heard from operations and maintenance staff at the conclusion of construction is, “This is exactly what I expected to be built and provided to us to operate and maintain.”

A.1.5 Case Specifics

This application case study describes the use of a standardized design process on a real project. The City of Atlanta hired CH2M HILL to design an expansion and improvements to its South River Water Pollution Control Center. Bidding and construction management services were also included in the contract.

This plant processes up to 30 million gallons per day of raw wastewater from a major portion of the City. The plant was originally built in the late 1980s. The continued growth of the tributary part of Atlanta and a tightening of the discharge standards made both an expansion and improvements to the plant a necessity. The capital cost of the constructed facilities was in excess of $150 million.

The scope of services referenced a Preliminary Design Phase and a Final Design Phase. The design delivery model used was able to accommodate this terminology and the associated scope of services yet retain the basic four phase approach described below.

A.1.6 Project Outcomes

The South River Water Pollution Control Center design project was completed successfully as were the bidding, construction and start-up phases. The plant continues to efficiently and effectively serve the citizens of Atlanta every day.

Major project achievements included:

- By the beginning of the Design Development Phase, the City's project manager and key management team members were using the four phase design delivery model terminology. They had requested and were given copies of the manual documenting the process. They were quickly able to appreciate the design related activities and were able to communicate their expectations in a manner that the design team readily understood. The City project manager and senior plant operators became integral members of the design team.

- Both design and construction of the WPCC were completed on time and under budget. Project quality was very high with few construction change orders. Start up of the constructed facilities went smoothly. More importantly, the operations staff knew exactly what they were getting and why key design decisions were made due to the extensive interaction during workshops. They are extremely happy with the plant facilities.

- The City was very pleased with the process and the service they received. Even before the project was completed, they awarded two more major design projects to the firm. The same four phase design delivery process was used for both. By the time these designs were fully under way, the City project manager and team members were so intimately familiar with the process that they were anticipating the next set of design activities and deliverables and providing proactive input for their completion. The City of Atlanta continues to be a valued client today.

- The City now expects similar documented standard project delivery processes from all its water and wastewater consultants.

- The four phased design delivery process used on the South River WPCC project is still in daily use at CH2M HILL. Although it has continued to evolve over time based on the lessons learned on every project, the core features of the process remain much the same.

- Because of the repeatability of this and similar processes, it is relatively easy to develop a database to record, track and trend design effort and costs on similar projects. The firm's design group has been able to reduce its average design effort by nearly 20 percent from 1992 to present. Universal use of the standard design delivery approach described herein is a key factor in this improvement along with the extensive use of 3-D modeling and state-of-the-art CAE tools.

A.1.7 The Four Phase Design Delivery Approach Details

An overview of this approach is presented above. The detailed description which follows is based on a typical design-bid-build delivery for a small or large water or wastewater treatment plant. It is intentionally general in nature. It is the design team's responsibility to add the details necessary for specific clients and projects. Some of the activities embedded in the process may not be applicable to the specific project. All of the remaining steps and activities need to be done to achieve success. However, the level of effort and detail to be expended on each must determined by the project manager and the design team leads.

Project Definition Phase

During the Project Definition (PD) phase, sufficient information is gathered to define the primary project goals and requirements. The starting point for PD depends on the project type and the level of initial planning that has already been done. If a preliminary engineering report has already been completed and endorsed by the client, the effort involved in this phase may be relatively minor. However, if the project is characterized only in the broadest of terms, the effort required will be much greater.

The end result is a clear statement of required performance with defined measures and evaluation criteria. Many data sources are required in this collection and analysis phase; they typically include the client, users, key officials, external requirements and standards, and the designer's experience. During the PD phase, the design team must avoid jumping ahead to detailed design solutions, and remain focused on the true goals of this phase — project definition.

Key Project Definition Phase Deliverables

During this phase of the work, PD package is prepared. At the completion of this phase, the design is often at a completion level of 3% to 5% of the total design.

- Project purpose/mission and success factors as defined by client
- Definition of external constraints
- Overall project delivery schedule
- Zoning and legal considerations
- Financing/funding limitations and requirements
- If not previously completed, "programming" of the project facilities. (This work product is often provided to the design team prior to the beginning of the design effort in the form of a conceptual or preliminary design report.)
- Project delivery approach

- Design and construction contract packaging
- Bidding and procurement requirements and any sole-sourcing restrictions
- Alternative project delivery methods
- Owner furnished or pre-purchased/pre-negotiated equipment
- Work plan including purpose, staffing, deliverables, budgets, and schedule
- Team charter
- Client design standards and preferences

Schematic Design Phase
The Schematic Design (SD) phase is the starting point for the project in the design process. In the previous Project Definition phase, the basic outline of the project was established to define the scope of the work. During the SD phase, a variety of design concepts are evaluated to determine the best solution for the project.

The objective of this phase of work is to identify and recommend the single concept that is the best solution to the design problem and to obtain the client's endorsement of it. It is critical that all major decisions be made, endorsed and frozen by the completion of this phase.

Various concepts are developed to solve the myriad of design challenges. These are evaluated and the most promising few presented to the client for their selection. Changes in the scope of services are a common result of this phase. A change management program is implemented during this phase and continues throughout the remainder of the design effort.

From a production standpoint, the SD phase is characterized by the development of rough sketches and very few low-detail CAD drawings. At this point, site, survey and plant performance data are being collected and organized into the base mapping CADD files of the project. However, most of the pictorial representations are sketches rather than CADD drawings.

Key Schematic Design Phase Deliverables
During this phase of the work, a schematic design report is prepared. The typical contents of this package are provided below. At the completion of this phase, the design is often at a completion level of 10% to 15% of the total design.

- Detailed process flow diagrams
- Process narratives
- Hydraulic profiles
- Preliminary equipment list/data sheets for major equipment
- Plant Utility mass/energy balances
- Preliminary site plan(s)
- Preliminary building floor plan sketches showing rooms and major equipment layout
- Preliminary building elevations
- Preliminary control system block diagram sketch and control philosophy

- Technical discipline design concepts (e.g., structural, electrical)
- Geotechnical report and final foundation design recommendations
- Parametric construction cost estimate
- Materials selection
- Documentation of all workshops and major decisions
- Checked calculations (internal deliverable only)

Design Development Phase
During the Design Development (DD) phase of the design process, a single concept is selected from a variety of alternatives. The conceptual design is refined and confirmed, and all major design decisions are made by both the project team and the client through workshops or other means.

Concepts developed and approved during the previous Schematic Design phase are considered fixed. Changes to these concepts constitute additional scope of work. Such changes are subject to Change Management evaluation prior to initiation.

From a production standpoint, the DD phase is characterized by the development of computer 3-D models or 2-D floor and site plans that serve as the base for future work. Electronic files are developed from schematic design sketches and, for some projects, enhanced into 3-D models. These models are completed and fixed at the conclusion of the DD phase, allowing for extraction of plans and sections from the project model, as necessary and without delay, by all design technologies at the beginning of the Construction Document phase.

Generally, during the DD phase, work progresses in distinct steps by alternating each design technology in succession. Typically, process, mechanical, and architectural and structural work predominates first, followed by I&C systems, building services, and site/civil. Toward the end of the DD phase, more electrical work efforts occur. A critical factor for project success (in terms of finance, schedule, and quality) is ensuring completion of all DD activities before proceeding to the Contract Document Preparation phase.

Key Design Development Phase Deliverables
The DD phase package typically includes a design development report, an updated construction cost estimate, and selected, partially complete plans and sections. The plans usually consist of P&IDs, major process equipment and piping, architectural and structural floor plans and elevations, site plans, and electrical one-line plans. If 3-D or advanced modeling techniques are used, there is also a collection of models. These are then used to aid client and internal QC reviews as it is often easier for people, particularly those who are not engineers or architects, to understand than 2-D drawings. Draft specifications also are included. At the end of the DD phase, the design is at a 45% to 55% completion level of the total design.

A typical set of DD deliverables includes:

- Final hydraulic profile
- Completed P&IDs (90%)
- Control system block diagram
- Equipment list
- Site/civil and site utility plans
- Preliminary electrical one-lines
- Building floor plans/elevations/major sections
- Exterior renderings
- Updated construction cost estimate
- First draft of specifications
- Documentation of all workshops and major decisions
- Checked calculations
- If 3-D modeling is used, the following deliverables are also included:
- 3-D modeling including building, equipment, and major piping
- Walk-through views of buildings
- Visualizations/renderings and other tools for public/agency review

Construction Document Preparation Phase
At the Construction Document Preparation (CDP) phase in the design process, all major client decisions have been made, and the work of previous phases is considered fixed. Changes from concepts already approved constitute additional scope of work.

From a production standpoint, the beginning of this phase is characterized by the ability of all multi-discipline design technologies to be able to work more independently from one another and freely without further client direction.

Key Construction Document Preparation Phase Deliverables
During the CDP phase, design plans, specifications, and supporting calculations are prepared to define the planned work for bidding and construction. The two major deliverables for this phase include the QC/client review documents and the 100% complete bid-ready documents. The QC/client review documents are pre-final and complete with the exception of minor fixes from compliance with QC and client review comments. The leads consider these documents as biddable before they are submitted to the QC reviewers and the client. This is the culmination of the effort of the entire design team.

A key internal deliverable, the postmortem report is also produced during this phase. This report should be completed within 60 days of completion of the design services.

If the QC/client review documents are complete, the final fix-up costs should not exceed 10 percent of the total design budget assuming the client makes no last minute changes. Projects that require greater efforts for fix up indicate that they were not properly completed or there was unbudgeted scope change.

The 100% design is a complete bid-ready package for reprographics and contractor pick-up. A properly completed 100% design is characterized by few, minor addenda during the Bid.

A.1.8 A Final Note

While this application case study focuses on a specific project, it is by no means unique. The process described herein had been and continues to be used successfully on hundreds of similar water and wastewater treatment plant designs. Variations of this approach are used every day for projects ranging from major Interstate highway improvements and expansions to hangars for military aircraft to power generation plants for private utilities to high tech manufacturing facilities across the globe. The project delivery vehicles include both traditional design-bid-build and engineer-procure-construct methods.

A.2 *Design Productivity Tracking Application Case Study*

A.2.1 Introduction

This case study is intended to further illustrate how successful Design Productivity Tracking efforts can be effectively implemented on projects. The Design Productivity Tracking DEP can play a very significant role in ensuring the overall success of capital projects.

A.2.2 Purpose and Benefits

Tracking design productivity is a useful way to benchmark design effort, identify opportunities for improvement, document key metrics and compare them to industry standards, and to develop cost estimates for future design efforts. As data is acquired over time it will indicate historical trends. It also facilitates quantitative assessment of the impacts of design efficiency improvements.

There are both internal and external benefits from the process and tools described above:

- Macro and micro productivity trends are readily observed - Productivity improvements by individual technical disciplines and design offices can be assessed. The impacts of design efficiency advances are illustrated in the trend graphs.
- Best Practices are identified – By evaluating the trends by each design office and technical discipline, management is able to identify any offices and groups that are performing in an exemplary manner or are not performing to the standard. Key design people in the top performing offices are then queried to identify the practices they use to be more efficient. If appropriate, these best practices are then installed throughout the rest of the organization. This capability also enables the productivity performance of offices to be compared. Because the differing office missions will drive the types and levels of people located there these comparisons need to be used with caution
- Reduced costs for preparing estimates for new projects - Using this approach has substantially reduced the level of effort and calendar time required to develop engineering design cost estimates. It also allows those that may otherwise have spent a great deal of time preparing estimates to work on projects for clients.
- Increased confidence in cost estimates – The level of accuracy of cost estimates prepared in this manner is much greater than those prepared in an ad hoc manner. This is due to the use of the historical data as a starting point as well as the application of a repeatable process which addresses all the key potential costs.

- Better client service – Clients have been very impressed with the ability to quickly create and adjust scope/pricing scenarios where other firms have had to take days to do the same. Having the trend data available also helps to assure the client that the firm has a proven system in place to efficiently deliver work.
- Excellent baseline – The documented scope, assumptions and estimated costs developed from the activities described above serve as an excellent baseline from which to practice change management. Both the client and the engineer have a clear, mutual understanding of the work products and services to be provided and the associated pricing.
- Benchmarking – It is easy to compare the major reported measures with that of the competitors in related industries.

While this application case study is focused on the use of a design productivity tracking method, many other Design Effectiveness Practices are reflected in the ultimate results. These include:

- Design Quality Management/QA/QC
- Integration of Lessons-Learned into Design
- 3D, 4D & XD CAD
- Design Automation & Software
- Virtual Teams
- Value Engineering in Design
- Vendor Integration & Design for Supply Chain

A.2.3 Approach and Methodology used at One Firm

CH2M HILL is a very large engineering design firm has been using this approach for more than a decade. It has a very distributed design operation with nearly two dozen medium to large design offices across North America. The approach it developed and has enhanced over time is presented here.

A.2.4 Consistent Structure and Delivery Approach

The consistent application of identifiable design phases is an important first step in developing a systematic tracking approach. To effectively develop and compare measures, the projects selected must also have a high degree of commonality. Example categories of projects are:

- Bridges
- Highways
- Chemical manufacturing plants
- General office buildings
- Microelectronic wafer fabrication plants
- Military facilities

- Municipal water and wastewater treatment plants
- Pharmaceutical manufacturing plants
- Power generation facilities

Each of these categories requires similar design disciplines and overall approaches. Another key aspect of productivity tracking is that the design delivery process must be defined, universally used and repeatable. Although all projects are by definition unique, employing identifiable steps that are common to each design allows different projects to be compared on a relatively equal basis. Finally, the project delivery approach must also be considered. The level and timing of design effort on a traditional design-bid-build delivery may vary markedly from that required for the same project delivered by a design-build or Engineer-procure-construct (EPC) method.

Applying a common work breakdown structure (WBS) to all design projects in a given category is also mandatory. It allows identical classes of cost data to be quickly gathered at the end of a project. Currently, CH2M HILL captures costs for each design phase at the individual discipline level to track the level of design effort and develop benchmarks. The engineering effort and costs expended during the bidding, construction and commissioning phases is also collected.

Data Compilation

At the completion of a design at this firm, the project manager or project controls specialist will complete a post mortem assessment. Among other information, they capture the effort and associated labor costs at each of the discipline levels for each design phase, expenses and the number of drawings produced. Project specific information such as the project category (see above), delivery approach used, which design office did most of the work, level of detail provided, and a general description of the scope is also compiled.

Other project specific data is captured to assist with detailed future costing efforts. For example, on a water treatment plant project information such as the source of the water, product water quality standards, unit treatment processes employed and the types of chemicals used is gathered.

Data gathered on projects executed outside the U. S. is converted to the equivalent US units for comparison purposes. This includes currency conversions.

To ensure the consistent compilation of the required information on projects, a data entry form tailored for the specific project category is used. This tool is Excel based and allows for the user to quickly record the key information about the project. The tool is dynamic in that the questions asked of the user are based on prior answers given. For example, if the user identifies that a filter was used in a water treatment plant, she will then be asked to provide input regarding type of system that was used.

The data entry tool is linked to a database that stores all the information gathered. There are separate databases for each project category although they are similar in structure. The database can then be queried to extract the information necessary to both analyze recent costs and plot trends. One database contains more than 200 similar projects completed as much as a decade ago. Others have fewer projects and may extend back only a few years because they represent newer market segments for the firm.

Data Analysis

The following are examples of the types of analyses made with the design phase data extracted from the database. These analyses are made within each design project category.

- Total design raw labor cost per drawing vs. number of drawings (overall and by technical discipline)
- Total design labor hours per drawing vs. number of drawings (overall and by technical discipline)
- Total expenses vs. total number of drawings
- Number of total bid drawings vs. construction cost (estimated or actual bid)
- Design cost vs. construction cost (estimated or bid)
- Design cost as percentage of construction cost vs. total drawings
- Constructed value per drawing vs. total number of bid drawings

The use of multiple parameters eliminates the potential to skew performance to improve any one parameter. For instance, it would theoretically be possible to produce twice the number of design drawings. This would cut the effort per drawing to about half which would normally be considered to be positive. However, it would have a similar impact on the constructed value per drawing which would be undesirable. The use of multiple parameters quickly highlights unusual areas of performance on a given project. It also enables the development of rules of thumb based on the average performance over a portfolio of projects. While these are not used to price future work, they are valuable for an overall assessment of the level of effort and pricing predicted using more detailed processes for a potential design project.

Comparisons are routinely made among similar delivery approaches and by design office. The intent here is to look for unusual variations. It also allows identification of groups that are very efficient. Their best practices can then be disseminated by the rest of the design organization to improve our overall efficiency.

In an effort to determine trends, the newest data is compared to the corresponding values from the previous update. These are typically made at six month intervals. CH2M HILL uses a three-year rolling project sample to track trends. The thought behind the 3-year cutoff is that its design efficiency approaches, techniques, technology and tools change rapidly enough that data older than this is of questionable validity. It also minimizes the impacts of monetary inflation. However, all of the data is retained in the database for historical reference. This allows the user to go back and look for similar projects that may have been completed for the same client more than three years ago.

The data for any individual update is basically a snapshot in time. Therefore, trends in key indicators are also plotted. This allows the design organization leadership to quickly identify areas of significant improvement and those that require some additional attention.

Over time the firm has seen its efficiency improve. These improvements are due to more effective and consistent design execution processes, computer aided automation and drafting advances, and increased overall competency of its designers. Step improvements for the introduction of CAD, 3-D modeling, and specific CAE tools in individual disciplines are readily discernable. For this firm, the average level of effort required to develop designs of similar complexity and scope today is approximately two thirds of that required fifteen years ago. While the level of effort has decreased, actual costs have risen slightly due to monetary inflation and salary escalation. However, the rate of increase is very low compared to the inflation index because the efficiency improvements have largely offset the inflationary pressures.

Reporting

A detailed report is prepared and distributed semi-annually to key internal stakeholders, the design organization's management team and the design staff. The purpose of these reports is two fold: to convey internally just how well it is doing both currently and over time, and to keep its design staff aware of the continuing need to be more efficient. Computing and trending costs allows the firm to compare its results to other independent performance benchmarks in the industry.

A.2.5 Application of the Data for Costing of Future Design Efforts

An Excel ™ based costing tool that utilizes the data and key metrics compiled was developed and has been used for that past seven years. This allows the estimated design costs for a potential project to be developed quickly and inexpensively. The user must understand the basic project scope and level of service to be provided. A list of givens and assumptions is developed. From this information and experience on similar projects, an estimated detailed drawing list is then prepared. This information is used not only to develop a projected cost but to negotiate a detailed scope with the client.

Once the definition is mutually endorsed, the drawing list is updated and the anticipated relative level of difficulty for each drawing is input. An initial design engineering cost estimate adjusted for inflation is automatically derived from this Excel ™ tool based on the most recent cost data. The person preparing the estimate and a senior reviewer then use their judgment to modify the estimate if needed. These modifications are usually relatively minor.

The resulting cost estimate is then compared to the key measures from the current database to determine if it seems reasonable. Once approved, it is then used as the basis for pricing of the overall project to the client.

A.2.6 Applicability and Flexibility

The model described above has been used on a wide variety of projects. It works for projects with total design efforts from 1000 hours up to those in the hundreds of thousands of hours. It is applicable to a wide variety of project types assuming that a reasonable data base has been developed and the project is "typical" for the data universe. It is also applicable to traditional design-bid-build and a variety of EPC project delivery methods.

As this approach evolves, productivity based on installed quantities in the constructed project will be added. An example is the number of hours spent by the structural designers compared to the cubic yards of concrete poured.

A.3 *Design for Constructability/Design for PPMOF Application Case Study*

A.3.1 Introduction

This case study (O'Connor, 2006) is intended to further illustrate how successful Design for Constructability/PPMOF (prefabrication, preassembly, modularization, and offsite fabrication) efforts can be effectively implemented on projects. As with many projects, the Design for Constructability and Design for PPMOF DEPs played very significant roles in ensuring the overall success of the capital Project.

A.3.2 The Project and Site

Alcoa, who is the is the world's leading producer of primary aluminum, fabricated aluminum and alumina, has whole or partial ownership of 27 smelting facilities worldwide with an annual manufacturing capacity of 4 million metric tons. The company is currently expanding to meet increasing demand, and the Fjarðaál Project was part of this growth. The Greenfield project involved construction of a 341,000 metric ton/year aluminum smelter in the municipality of Fjarðabyggð, located on the east coast of Iceland. As part of a national initiative for economic diversity, the project was coupled with a MWe hydroelectric station developed by Landsvirkjun (the national power company), and a new harbor facility constructed by the Fjarðabyggð municipality. There were also improvements to roads and other community infrastructures in the region. Upon completion, the project represented one of the largest private-sector investments in Iceland's history and one of the cleanest aluminum production facilities in the world, incorporating new technologies to promote sustainability and minimize environmental impact.

A day's drive from Reykjavik, the aluminum plant is located 5 km east of Reyðarfjörður, which is comprised of 670 inhabitants and is located adjacent to eastern Iceland's largest fjord, offering prime conditions for Panamax-class vessels moving alumina to the smelter and aluminum products to market. Approximately 3,000 inhabitants live within the municipality of Fjarðabyggð, which encompasses Reyðarfjörður and has an economy driven by fishing, tourism and farming. The Fjarðaál site slopes from steep mountains into the fjord, and was once used for farming and grazing of Icelandic horses.

Aluminum smelting is the process of extracting aluminum metal from aluminum oxide (alumina) through electrolytic reduction. The fundamental component of a smelting operation is the electrolytic cell, or "pot" in which this reaction takes place. During smelting, large amounts of current pass through molten alumina dissolved in a 950° C cryolite bath. This process separates out aluminum metal for removal and casting.

Smelters typically operate hundreds of pots, linked electrically in configurations called potlines. Thus, efficient and economical power plays an important role in the business case for smelting, along with access to deep water as both raw materials and finished products traditionally ship by marine transport.

Alcoa Fjarðaál's goal was to design and operate an aluminum smelter at the leading edge of environmental performance. The completed project met new European environmental standards years before they came into effect. Alcoa also designed the plant so as to eliminate all discharge of process water into the sea, as the importance to Iceland of safeguarding its marine environment cannot be overemphasized. Spent pot lining, which is a byproduct of sustained pot operation, contains hazardous materials and is being recycled in purpose-built facilities outside of Iceland. From among more than 2,000 worldwide corporations Alcoa was recognized in the Global 100 Most Sustainable Corporations in the world by Corporate Knights of Toronto for their ability to meet the "triple bottom line," a measure of value that balances the environmental, social, and economic impacts of a business.

A.3.3 Scope and Objectives for Constructability on Fjarðaál

Constructability is a work process where members of the construction group work closely with their engineering and procurement partners to assess best practices, innovations and new technologies while creating the most efficient project execution strategy. On any new project, and especially for large complex capital developments, Constructability is an essential process for identifying value and is part of the project "toolbox" for delivering predictable results.

Constructability is an interactive practice that drives value by finding execution options during the window of optimum influence (such as before detailed engineering accelerates to full production), and can be distilled into the components of acquiring data, evaluating consequences, and incorporating beneficial ideas.

Constructability was an integral part of the Fjarðaál Project from its inception. The Fjarðaál Constructability Program was designed using Bechtel corporate standards, Six Sigma, CII guidelines, and the principles of Alcoa Business Systems. Through this comprehensive effort the program identified significant capital reduction opportunities for the project through optimization, construction efficiencies, preassembly, standardization, and cycle time reduction.

The constructability program objectives for the Fjarðaál Project were targeted as follows:

- Enhance the integration of engineering, procurement and construction from initial planning to mechanical completion and turnover.
- Develop the optimum path of construction considering the critical path, major equipment, climatic influences and best use of construction resources.

- Incorporate safety in design considering the risks of smelter construction, unique site conditions and customs/practices of a diverse workforce.
- Incorporate Lessons Learned, Best Practices and suggestions from past and present projects as well as from the Fjarðaál team.
- Develop a plan to recycle, reuse or eliminate construction byproducts and set a new standard for waste minimization.
- Reduce the complexity of construction through workface planning and effective logistics that compliment performance.
- Optimize construction indirects through common use of services, facilities, and equipment across the site.
- Explore construction techniques and technologies that create value in terms of safety, quality, cost, schedule and sustainable development.
- Support other related value efforts such as the EPC Integrated Schedule and plans for Preassembly, Logistics, Work Packages, and Pre-commissioning.
- Build teamwork and shared expectations that enhances performance throughout the project.

A.3.4 Program Responsibilities

The Project Manager and Site Manager were responsible for enabling Constructability on the Fjarðaál Project. A program plan was developed and all team members were provided an orientation reflecting processes and benefits, and were subsequently encouraged to participate throughout their realm of expertise.

The heart of Constructability was conducted during the project's planning phase which enveloped the optimum window of influence. A dedicated Constructability Coordinator was responsible for implementing the process to nurture, harvest and deliver results that could be readily incorporated into engineering and procurement streams without hindering the production of detailed design or equipment/material acquisitions.

Upon completion of the planning phase and after the authorization to proceed with project execution, the Project Field Engineer carried Constructability forward and was responsible for the program through the balance of detailed design and onto the jobsite. Although this stage of the program offers less opportunity as it resides outside of the optimum window of influence, it nonetheless is essential towards sustaining robust communication regarding the details of construction, as well as enabling the use of best practices and evaluation of new work processes.

The progress of Constructability was routinely communicated to the project team in order to status advancement towards goals and objectives, while also recognizing the efforts and employees that generated recognizable value to the project. The importance of acknowledging team accomplishments cannot be understated, and is proportional to harvesting new ideas and optimizations. On the Fjarðaál Project, The Constructability

Coordinator and Project Field Engineer were accountable for effecting timely acknowledgements throughout their respective program responsibilities.

A.3.5 Work Process Overview

To initiate the process a dedicated Constructability Coordinator designed the program objectives with the project's Leadership Team (i.e.; Alcoa and Bechtel Project Managers and responsible managers for engineering, procurement, construction and controls) and set specific goals that were appropriately resourced. The Constructability Coordinator then meet with functional teams to review lessons-learned and best practices relating to each discipline using sources such as Alcoa/Bechtel Knowledge Banks and other industry related data sources. A Constructability Input Form (see Attachment A) was developed to provide a platform to mine ideas from the team, and a Constructability Log (Attachment B) was maintained for capturing idea descriptions, initiators, potential value, and status.

A review of design documents was conducted throughout this effort and the Constructability Coordinator initialed check prints as reviews were completed. To effectively support all disciplines, Field Engineers and/or Craft Superintendents with specific expertise were frequently brought into the team to enable Constructability reviews while supporting the progress of detailed design.

Sponsors of the Constructability Program included the project Leadership Team and select others with particular knowledge or experience. These sponsors were responsible for providing the energy for Constructability in a manner that encouraged team participation while in parallel sustained the progress of project planning and detailed design. To that end, Constructability on Fjarðaál was intended to complement the design process through integration of construction processes and innovations, while precluding the recycling engineering - as the downstream consequences from revisiting completed design are usually more costly than the potential savings.

The process for evaluation and approval of Constructability input resided with the Leadership Team, with the overall authority resting with the Project Manger. Evaluation of input was focused on forecast value (or related benefit), ease of incorporation, and addition or reduction of risk. Emphasis was also placed on:

- ⇨ Designing and planning to reduce field erection hours
- ⇨ Dividing work into packages to optimize construction efficiency
- ⇨ Incorporating Environmental, Safety & Health (ES&H) requirements, resources, and logistics
- ⇨ Mitigation of climate/weather influences (e.g., wind, precipitation, -and the swing of daylight from summer to winter)
- ⇨ Increasing the probability of delivering predictable results.

Other key elements to support Constructability included the following:

- ✓ Constructability Meetings, where both planned and ad hoc sessions were conducted to review facilities layout, construction processes, standard details and specifications, and applicability of new ideas and innovations.
- ✓ Review of Design Documents, with a focus on construction efficiencies that result from standardization, preassembly, and consideration of field erection logistics such as interface with adjacent work operations and optimization of construction indirects.
- ✓ Participation in the creation and review of Purchase Orders in order to apply constructability objectives and opportunities to supplier products and services, such as exploring options for shop assembly and testing, and determining optimum logistics for material transport and staging. Supplier engagement and participation was integral to this effort.
- ✓ Testing the flow of EPC products by working from “required at site” dates back through each upstream cycle to assure suitable time was allowed for each stage including design, purchase, and delivery to site.
- ✓ Close integration with the ES&H Management Plan to incorporate safety and environmental considerations into design, including identification of probable by-product generators and work processes for reuse or recycle.
- ✓ Identification of bulk materials that provided the best value to the project, considering initial cost, ease of installation, cycle time from suppliers and known high value products. Examples include fasteners, anchors, pipe fittings, electrical connections, raceway, and supports.
- ✓ Periodic recognition of team members who contributed to the success of the Constructability Program.

A.3.6 Program Timeline

A summary relative timeline for implementation of the Fjarðaál Constructability Program is provided below:

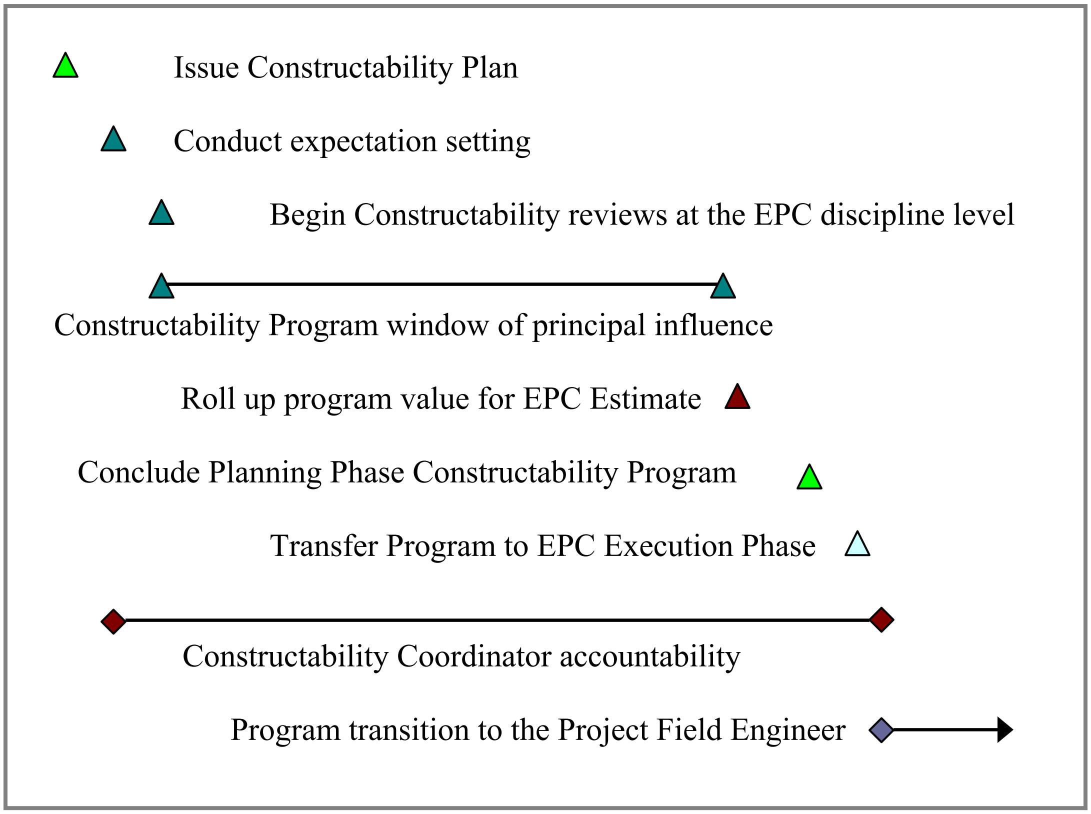


Figure A.2: Relative timeline for implementation of the Fjarðaál Constructability Program

A.3.7 Select Constructability Program Elements

A more detailed review of a few key value operations follows.

Discipline Workshops

To achieve alignment on preferred EPC practices while evaluating new ideas and technologies, the Fjarðaál Project conducted a series of workshops with engineering, procurement and construction representatives at the discipline level (i.e.; civil, electrical and mechanical). This tight focus allowed for specific details to be worked out that in turn drove timely decisions that mitigated recycle. Different from more global constructability reviews (e.g.; industry based lessons learned), the Discipline Workshops allowed the respective team members to identify and resolve issues/opportunities on a task level.

To facilitate these reviews without interrupting the daily production of work, Discipline Workshops were typically conducted during off hours in a setting appropriate for seeding new ideas. Although this initiative required an investment of additional hours and a facility, the corresponding value harvested by the project more than offset the cost, thus confirming that good work processes deliver tangible results.

A common theme was used for these workshops, based on the following principles:

- ☑ *Simplicity and Standardization* – repeatable work operations enhance efficiency and fewer field assemblies equal less man-hours
- ☑ *On the Ground* - performing work on the ground is safer and more efficient than in the air, and can also be cheaper due to fewer demands for indirects.
- ☑ *Build Off Site* - site labor costs and field conditions in Iceland can be more costly than within an controlled shop or yard (offsite)
- ☑ *Permanent for Construction* - utilizing permanent facilities for construction prevents duplication and disruption
- ☑ *Construction Sequencing* – aligning construction continuity, seasonal influences and labor availability maximizes efficiency and productivity
- ☑ *Material Management* - efficient control of materials is critical to success, and especially so for remote sites

In addition to these common principles, target focal points were developed for each discipline to enable the EPC team to advance the planning of work before detailed design passed the window of influence. Examples of these targets include:

Civil

Concrete	**Coatings**	**Fasteners**	**Formwork**	**Rebar**
Cladding	**Embeds**	**Flashing**	**Penetrations**	**Steel**

Electrical

Cable	**Circuits**	**Grounding**	**Lighting**	**Preassembly**
Cable Pulls	**Equipment**	**Fasteners**	**Penetrations**	**Terminations**

Mechanical

Cranes	**Modules**	**Preop**	**Shipping**	**Tolerances**
Lubrication	**Preassembly**	**Rigging**	**Testing**	**Vendor Reps**

By all accounts, the Discipline Constructability Meetings were very successful. The engineers gained a better understanding of what they could do to make construction more efficient, and Construction better understood the challenges facing engineering. As a result, the team gleaned a host of constructability input suggestions via the process.

PPMOF/Preassembly

Traditionally, the preassembly of components for aluminum smelters is not at a level common to other processes such refineries, however due to the high cost of construction in remote locations an early project initiative sought to maximize preassembly and hence the relocation of work from the site.

The basic premise driving preassembly is reduction of site labor hours that by nature also reduces the high cost of indirects germane to a remote site, specifically the costs associated with transportation and accommodation of the workforce. Preassembly also decreases the impact of construction on the community, including the reduction of waste byproducts. It also lessens the risk encountered by skilled resources, as the work is performed in shops or regions where labor is readily available. The project took an aggressive approach to preassembly in order to reduce the demand for onsite resources while optimizing cost efficiency. Through development and use of an interactive Preassembly work process, the Fjarðaál Project evaluated, planned, scheduled and tracked each potential preassembly package until a suitable business case could be determined. This effort resulted in all project groups working in concert to support the initiative of maximizing the size and assembly of equipment, frames, skids and modules to the site.

The results of this effort allowed a noteworthy volume of construction hours to be performed offsite, which in turn reduced project cost, preserved schedule contingency (through parallel progress), and lowered the risk in acquiring, transporting and accommodating skilled resources.

EPC Integration

There is no substitute for becoming involved with the Engineering, Procurement and Construction process when it comes to integrating constructability into the project. An active constructability program allows crisp definition of the handoffs between engineering, procurement and construction, which in turn increases the probability of efficient, cost-effective and on-time project completion. Considering that today's projects are executed in a global EPC environment, integration of the development team is essential to meeting customer business objectives. In response, constructability can act as the integrator of project deliverables up to the handoff of care, custody and control to the facility operator.

Attributes of EPC integration derived from constructability included the following:

- Defining standard and project specific deliverables from the engineering and procurement teams to construction.
- Delineating key project milestones that support an efficient path of construction that consider both global and site specific influences to performance.
- Establishing a robust pipeline for communication between EPC partners, that is seeded early in project planning and harvested throughout construction.
- Expanding the prospect of value adding options through interactive EPC reviews of new processes, technologies and solutions to old problems.
- Incorporating opportunities such as preassembly or process modeling to overcome site and project specific challenges to the business case.

- Participating in the formation of material requisitions to ensure that constructability expectations are understood by bidders including the use thereof in determining total installed cost (TIC), and evaluation of bids.
- Identification of and contribution to the development of standardized specifications that would enhance constructability of the design.
- Contribution to planning and scheduling to ensure that constructability initiatives were embraced by the engineering and procurement partners.

To queue up constructability for success, the Constructability Coordinator must be supported by EPC management as well as other project-specific stakeholders, such as Area Managers, preassembly sponsors and the site construction team. An experienced constructability team made up of Construction Supervision, Field Engineering, Material Management and others must interlock with the engineering and procurement organizations to deliver integration within the EPC project. This teamwork develops over time and creates “Constructability Converts” rather than imposing one part of the organization over the other.

Constructability Suggestion Program

Through the course of project planning on Fjarðaál the Constructability Suggestion Program netted over 140 constructability suggestions covering a range of opportunities from optimization of standards to leading edge innovations. Examples of the ideas harvested from the suggestion program include:

- Standardized formwork
- Standardized fastener sizing
- Composite Claustra walls
- Simplified Raceway hangers
- Extensive Busbar preassembly
- Precast concrete
- Narrow gap welding
- Pre-engineered buildings
- Rebar spacing and cover
- Bolted hanger clips

The Fjarðaál Constructability Newsletter served as an excellent device for communicating innovations and sharing recognition with deserving participants. As the project moved into execution and throughout construction, fresh ideas continued to be harvested.

A.3.8 Top 12 Value Initiatives

Coalescing input from previous aluminum smelter projects, suggestions from team members , and actions derived from the discipline constructability meetings, a prioritized roster of project specific opportunities was developed based on their value to capital and urgency related to the incorporation cycle time. This input was distilled into the “Top 12

Fjarðaál Value Initiatives," that by definition represented opportunities to bring substantial value to the Fjarðaál Project through saving field hours, enabling a safer work environment, improving efficiency and mitigating risk.

The Top 12 Value Initiatives for Fjarðaál included:

1. Permanent for Construction Task Force: reducing indirects through use of permanent facilities and systems for construction

2. Utility installation parallel with earthworks: creating the optimum process for installing utilities

3. Pot lining Task Force: detailing a highly repetitious work process for cycle time improvements

4. PPMOF/Preassembly integration: designing for preassembly instead of adding a layer on top of standard practices

5. Power & Free Conveyor Installation: optimizing the installation of a highly complex material conveyance system

6. Constructability Guide initiative: instructions on how to incorporate value while not interrupting production

7. Cladding installation: selection of roofing and siding systems than minimize at height work and optimize mechanical fastening

8. Concrete work process: enabling a fresh view of concrete placement to maximize labor efficiency

9. Coating specification: similar to concrete, selecting coating products and systems that minimize onsite labor requirements

10. Hydraulic packages: standardizing the design of hydraulic power units and related piping systems

11. Ductwork standardization: reducing the cost of installation through repetition

12. Constructability and Material Requisitions: incorporating constructability expectations into the material requisitioning process

It was decided to energetically pursue these Top 12 Value Initiatives at the project level, and the Area Project Managers were assigned as sponsors of the initiatives within their geographical jurisdiction. Each of the Top 12 was also assigned a champion who was involved in the actions and led the initiative through to completion.

The Top 12 were published as large graphic posters that were displayed on the walls around the project and site offices. These posters listed the plan, the goals and the measurement of success to be used in managing this important project initiative.

A.3.9 Conclusions

The Design for Constructability and Design for PPMOF design effectiveness practices were an integral part of the Fjarðaál Project as both the facility owner, Alcoa, and the project developer, Bechtel, envisioned the value that could be derived from an early and robust program. As outlined here, constructability and PPMOF were embedded during inception of the planning effort, a choice that resulted in the process being seamlessly integrated without interruption to the vital production of design documents and procurement activities.

The Fjarðaál Constructability/PPMOF Program delivered results measured at several million dollars in direct savings, and substantially more through mitigation of risk. The primary areas for which added value was realized included the following:

- *Cost of construction*: approximately 10% reduction in direct and distributable field costs was realized by implementing the full suite of constructability elements described within this case study.
- *Mitigation of safety and health risk*: Early planning and process review substantially contained the potential for exposure.
- *On-time delivery of production facilities*: Constructability was key to allowing the owner/operator to enter the marketplace as planned.
- *Protection of contingency*: Solutions were created that responded to specific site challenges, such as weather, where interruptions at peak staffing could have affected construction progress at a cost of approximately $1 million per day.

Such added value was achieved through such constructability program elements as preassembly, standardization and cycle time reduction, all by a team focused on delivering at the next level of performance. If a dedicated constructability program had not been initiated on the Fjarðaál Project such opportunities would not have been realized and the high cost of variable risk would have encroached upon the capital business case.

A.3.10 Acknowledgements

The author and the Construction Industry Institute gratefully acknowledge the significant contributions of the Alcoa and Bechtel Fjarðaál Project constructability program

participants and project managers in sharing this project case study and in assisting in its preparation.

<table>
<tr><td colspan="3">Fjarðaál Project
Constructability Input</td><td colspan="2">Number:
Date:</td><td colspan="3"></td></tr>
<tr><td colspan="2">Initiator:</td><td colspan="6">Dwg/Spec
Reference:</td></tr>
<tr><td colspan="8">Existing Condition:</td></tr>
<tr><td colspan="8">Suggested Alternative:</td></tr>
<tr><td colspan="8">Rationale:</td></tr>
<tr><td colspan="8">Attachments or Reference Documents:</td></tr>
<tr><td colspan="2">Forecast Value:</td><td colspan="2">$</td><td colspan="3">Reduced Hours (state E, P or C):</td><td>hrs</td></tr>
<tr><td colspan="2">Ease of Incorporation:</td><td colspan="2">☐ No Impact</td><td colspan="4">☐ Impact to be evaluated (identify plan below)</td></tr>
<tr><td>Risk:</td><td colspan="2">☐ None</td><td colspan="2">☐ Decrease</td><td colspan="3">☐ Increase (identify plan below)</td></tr>
<tr><td colspan="8">Impact or Risk Mitigation Plan (ES&H, Schedule, Cost, Quality, Climate):</td></tr>
<tr><td colspan="2">Suggestion Approved:</td><td>Engineering</td><td colspan="2">Procurement</td><td colspan="2">Construction</td><td>PM</td></tr>
<tr><td colspan="2">Suggestion Incorporated:</td><td colspan="4">By</td><td colspan="2">date</td></tr>
</table>

Figure A.3: Constructability Input Form

Fjarðaál Project Constructability Log					
Number	**Date**	**Initiator**	**Description**	**Value**	**Status**

Forecast Value This Page: $

Figure A.4: Constructability Log

Appendix B:
Key Drivers of Design Quality and Productivity

1. Accurate understanding of owner project priorities and objective-preferences (including tradeoff preferences).

2. Detailed definition of project work scope that has been both committed to (i.e., signed-off) by all key owner stakeholders and adequately challenged by the design team.

3. Accurate understanding of existing site conditions, including access to (or ability to develop) accurate as-built information.

4. Awareness of, and timely access to, all key project stakeholders.

5. Timely input into the design process from all key stakeholders.

6. Sufficient awareness of all design phase related interface requirements and timing constraints, including:

   a. Knowledge of owner-driven critical completion or need dates.
   b. Knowledge of owner design and procurement approval processes and durations.
   c. Knowledge of regulatory jurisdiction approval processes.
   d. Knowledge of owner-furnished equipment and related access availability.
   e. Knowledge of owner's existing supplier alliances and supply chain integration processes and agreements.
   f. Knowledge of owner's planned shut-down dates for existing facility and knowledge of operations requirements near phased construction work.

7. Adequate design team leadership.

8. A sufficiently detailed project execution plan prepared by key project team managers and understood and committed to by the design team.

9. Sufficient resources that are funded and provided in a way that they can be deployed in an efficient manner.

10. Presence of sufficient design team experience pertaining to any unique project elements (e.g., new material/fabrication/construction technologies, new manufacturing processes, etc.).

11. Awareness of, and access to appropriate design software tools.

12. Safe and comfortable working conditions that promote a productive environment.

Appendix C: Design Effectiveness Practice Characterizations

This appendix provides a brief characterization of the 30 design effectiveness practices (DEPs), including an overview of practice objectives, key benefits, influence on project value objectives (PVOs) that is used in the practice selection tool, a review of the practice history and maturity, commonality of the practice, best circumstances for evaluation, limitations, linkage with design effectiveness (DE), and recommended resources for further exploration. Practice characterizations are broken into two groups. The first group of 10 focuses on design strategies and management, and can be considered as broad efforts that may be best deployed at the organizational level to support multiple projects (although they can be deployed on a per project basis). The second group of 20 practice characterizations describes specific techniques and methods that are focused on a particular objective. They can be deployed on a per project basis, although organizations may lack expertise for a specific practice. The characterizations below are meant to be an overview and starting point for further examination of a practice.

DESIGN STRATEGIES & MANAGEMENT

1. Standard Design Delivery Process

1. **Practice Objectives**
   Through the development and maintenance of a standard design delivery process and effective contractual vehicles, promote efficiency and quality control during the design phase, resulting in quality constructed facilities.

2. **Key Benefits**
   Practice provides for the continuous improvement of facility design and construction through the incorporation of lessons-learned. Makes the design process more predictable and enables standardized QA/QC procedures tied to specific design milestones, thereby improving the quality of projects.

3. **Influence on Project Value Objectives**
   - Regulatory & Standards Compliance ...... + +
   - Capital Cost Reduction .... +
   - Product/Plant/Service Quality .... +
   - Design & Construction Quality .... + +
   - Schedule Reduction .... +
   - Environmental Stewardship .... +

4. **Practice History/ Maturity**

   The practice is very mature. Standardization of the design process, in its most traditional form, identifies three design phases: schematic design, design development, and construction documents. The standard design delivery method was pioneered by the American Institute of Architects, most notably in their standard forms of agreement for architectural services, and has been widely recognized and adapted by major design and construction related organizations. Variations of the design delivery process are utilized in design-bid-build, design-build, fast-tracking, and other project delivery methods that increasingly overlap the design and the construction phases. Mature design organizations often build from the basics to have detailed design delivery process that is customized for specific project types.

5. **How Common**

   This practice is common in all sectors of the design and construction industry.

6. **Best Circumstances for Application**

   Benefits from this practice are leveraged when one or more of the following circumstances exist:
   - No standard design work process exists for an emerging project type, or an existing process needs updating.
   - New contract/delivery process or new technology, or recent major industry event prompts the need for a new or modified design process.
   - Owner requests a design process model.

7. **Limitations and Pre-Requisites**

   Practice may cause a lengthy design and review process. Not necessary for projects replicated from completed "standardized" designs. In these cases, a completed design may only require modification to accommodate unique site conditions or desired minor deviations.

8. **Linkage with DE**

   The optimal utilization of a standard design delivery process can enhance design effectiveness when properly applied.

9. **References**

   - AIA (2005) *The Architect's Handbook of Professional Practice*, *Volume 2 The Project.* AIA Press, Washington, D.C.
   - Bowers D.; Bhargava, R; and Anderson, S. (2003), "Characteristics of Integrated Project Delivery and Contract Strategies" *RR165-11,* Construction Industry Institute, Austin, TX.

2. Design Quality Management/QA/QC

1. Practice Objectives

The objective is to find an optimum balance between quality and minimized cost, and improve project consistency, clarity and accuracy while eliminating errors, conflicts and omissions. Customer requirements and expectations are satisfied. Accountability and efficiency are emphasized. This practice should be repeatable. The focus of this practice includes TQM, Quality Function Deployment (QFD), and continuous improvement.

2. Key Benefits

Repeatability of the design process and outcomes (e. g., ISO certification) is expected. Mapping of the design processes documents approaches used and serves as basis for future improvements and enhancements. Redesign costs are reduced which in turn reduces the overall design costs. Construction costs are also lowered through elimination of errors during design phase. Construction claims are reduced resulting in lower capital costs. Well followed QA/QC processes can increase effectiveness and reduce required costs and level of effort. Operational effectiveness and efficiency of constructed systems is enhanced. Improvements happen on a near-continuous basis resulting in evolutionary and occasionally revolutionary improvements over time.

3. Influence on Project Value Objectives

- Security .... +
- O&M Safety .... +
- Construction Safety .... +
- Regulatory & Standards Compliance .... + +
- Capital Cost Reduction .... +
- O&M Efficiency .... +
- Product/Plant/Service Quality .... + +
- Design & Construction Quality .... + +
- Schedule Reduction .... +

4. Practice History/ Maturity

Theory dates back to the early 1900s. The practice was used in auto manufacturing industry by Japan after WWII. ISO 9001 is the only quality assurance model in the ISO 9000 series that addresses the design element. More recently, CONQUAS (CONQUAS, 2001), a quality measurement instrument employing performance measurement and benchmarking techniques was developed by the Singaporean Construction Industry Development Board (CIDB, now the Building and Construction Authority – BCA).

5. **How Common**
   This practice is very common among industry sector leaders. All design activities need a formal checking procedure to eliminate errors.

6. **Best Circumstances for Application**
   This practice is fundamental to every design effort. Benefits from this practice are leveraged when one or more of the following circumstances exist:
   - Formal design verification is required by the owner.
   - Insurance savings may result or liability risks can be mitigated.
   - Recent related code changes have occurred.
   - Design team has limited experience with related technologies.
   - Field changes during the construction and operations phases are extremely expensive and undesirable.

7. **Limitations and Pre-Requisites**
   The practice requires the investment in initial development of objectives, solutions, processes, procedures and tools. "Quality" is hard to define and is often industry, market, client and firm specific. Metrics are often difficult to develop and measure. Quantitative assessment of financial benefits is challenging. Implementation requires special expertise.

8. **Linkage with DE**
   The ideal design will be clear, concise, well coordinated across all technical disciplines, comply with all current codes and standards and achieve all client criteria and expectations. An effective quality management program can help achieve these goals while helping control costs. This includes redesign costs as well as those for changes made during construction or after operations commence.

9. **References**

   - Akao, Y., (1990). *Quality Function Deployment: Integrating Customer Requirements into Product Design*, Productivity Press, New York;
   - CII (1987) "Input Variables Impacting Design Effectiveness", *RS 8-2*, Construction Industry Institute, Austin TX.
   - CII (1989) "Costs of Quality Deviations in Design and Construction", *RS 10-1*, Construction Industry Institute, Austin, TX.
   - CII (1989), "Measuring the Cost of Quality in Design and Construction", *RS 10-2*, Construction Industry Institute, Austin, TX.
   - CII (1990) "The Quality Performance Management System: A Blueprint for Implementation", *RS 10-3*, Construction Industry Institute, Austin, TX.
   - CII (1994), "Measuring Quality Performance on EPC Projects", *RS 36-1*, Construction Industry Institute, Austin, TX
   - CII (2001) "Engineering Productivity Measurement", *RS 156-1*, Construction Industry Institute, Austin, TX.

- Fox, A.J. and Cornell, H.A., (1984), *Quality in the Constructed Project,* American Society of Civil Engineers, New York, NY.
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- Marosszeky, M. and Karim, K. (2002) "Enterprise process monitoring using key performance indicators" *Design and Construction: Building in Value*, Elsevier Science Ltd., Oxford, pp. 276-290;
- Nee, P. A (1996). *ISO 9000 in Construction*, John Wiley & Sons, Inc., New York;
- Oswald, T. and Burati, J. (1992). "Identifying Customer Requirements Through Quality Function Deployment", *SD-69*, Construction Industry Institute, Austin, TX.
- Oswald, T. and Burati, J. (1992). "Guidelines for Implementing TQM in the Engineering and Construction Industry", *SD-74*, Construction Industry Institute, Austin, TX.
- Oswald, T. and Burati, J. (1993), "Adaptation of Quality Function Deployment to Engineering and Construction Project Development", *SD-97*, Construction Industry Institute, Austin, TX.
- Stevens, J.; Ledbetter, W.; and Glagola, C (1992). "Quality Performance Measurements of the EPC Process: Current Practices", *SD-79*, Construction Industry Institute, Austin, TX.

3. Design Standardization/Process Industry Practices

1. Practice Objectives

Improve the effectiveness of the constructed design and the efficiency of the design process by implementing a set of standard design solutions, industry practices, and product and material selections for recurring situations.

2. Key Benefits

By standardizing successful solutions to common design problems, new projects can benefit by minimizing problems with those standardized design components. Starting a project with an array of standardized, cost effective design components can help to assure overall project success. Standardizing product selections can also set the stage for advantageous purchasing agreements between owners and commonly used vendors and suppliers.

Design standardization also reduces:

- Time and effort in the design phase
- Commissioning and qualification effort
- Training requirements

- Maintenance costs and spare parts inventories

3. Influence on Project Value Objectives

- O&M Safety .... +
- Construction Safety .... +
- Regulatory & Standards Compliance ...... +
- Capital Cost Reduction .... +
- O&M Efficiency .... +
- Product/Plant/Service Quality .... +
- Design & Construction Quality .... +
- Schedule Reduction .... +

4. Practice History/ Maturity

This practice has been around for decades in the form of standard details, corporate standards, standard equipment selections, etc. The Process Industry Practices organization (focused on design standards) has been in existence since 1993 as a separately funded initiative of CII.

5. How Common

Practice is quite common among A/E firms and large owner organizations.

6. Best Circumstances for Application

Benefits from this practice can be achieved when one or more of the following circumstances exist:

- The project has repetitive complex components.
- The project is for a large organization with multiple similar facilities, or is a common project type within an industry sector.
- The project requires high levels of regulatory qualification and/or inspection.
- Projects with a high cost or high consequences of downtime (i.e. life safety, revenue, system service, etc.).

7. Limitations and Pre-Requisites

This practice requires that:

- The design team has access to an knowledge of a library of successful component designs, industry practices and product and material selections.
- The design team has access to information regarding project location influences such as climate, bidding environment, trade availability, trade skill levels, and differences in regulatory requirements that may influence the selection of standardized designs and products.
- The design team's organization periodically challenges the standardized designs and products as technology and construction methods evolve.

8. **Linkage with DE**
   Appropriate implementation of design standards can greatly enhance the effectiveness of both the design process and the constructed design.

9. **References**

   - PIP (2002), "Architectural and Building Utilities Design Criteria", *ARC01015,* PIP Pub, Austin, TX.
   - PIP (2005) "Civil Design Criteria", *CVC01015*, PIP Pub, Austin, TX.
   - Process Industries Practices website: www.pip.org [accessed 06/28/2007]

4. Integration of Lessons-Learned into Design

1. **Practice Objectives**
   Leverage experience by communicating with subsequent projects on specific problems and successes. Reduce cost and schedule, improve quality by sharing problems experienced on other similar projects. Reduce construction and operational risk by incorporating investigation results from safety incidents into future design, procurement and construction practices.

2. **Key Benefits**
   Potentially improves all project value objectives when lessons learned are comprehensive relative to the projects and topics that they cover.

3. **Influence on Project Value Objectives**
   - Security .... +
   - O&M Safety .... +
   - Construction Safety .... +
   - Regulatory & Standards Compliance ...... +
   - Capital Cost Reduction .... +
   - O&M Efficiency .... +
   - Product/Plant/Service Quality .... +
   - Design & Construction Quality .... +
   - Schedule Reduction .... +
   - Environmental Stewardship .... +
   - Flexibility for Future Use .... +

4. **Practice History/ Maturity**
   Practice has been performed informally throughout construction history. Formalization began about 30 years ago. Recent history added automation tools to facilitate practice.

5. **How Common**
   Practice is very common in industrial sector projects. Large firms have automated database systems.

6. **Best Circumstances for Application**
   Benefits from this practice are leveraged when one or more of the following circumstances exist:
   - Large organization with broad EPC or turn-key like breadth of scope.
   - Company culture is receptive to experience sharing.
   - Project involves many first-time participants.
   - Lessons-learned are documented and can be shared.
   - Use of repetitive or high volume elements or components.

7. **Limitations and Pre-Requisites**
   Companies with Lessons Learned programs may be reluctant for competitive reasons to share them with other project participants where the contracting vehicle is not EPC. Short term and small contracts create a perception of insufficient time or budget to implement LL. Prerequisites for implementing a LL program include a going concern that repeats project types or elements, an organizational desire to improve performance and management commitment at the company and project levels.

8. **Linkage with DE**
   A successful application of a Lessons Learned program will eliminate repeat problems. It has the potential to improve all project construction parameters and can be applied to activities in Engineering, Procurement, Construction, Startup, Operations, Maintenance and Closure/Decommissioning. Most benefits can be achieved only if the changed conditions resulting from the lesson are reflected in the design, purchasing documents, or construction/startup procedures.

9. **References**

   - CII (1997) "Modeling the Lessons Learned Process", *RS 123-1*, Construction Industry Institute, Austin, TX.
   - Tatum, C. B and Reuss, M. C. (1991) "Construction Experience Transfer", Center for Integrated Facilities Engineering, September.

5. Change Management

1. **Practice Objectives**
   This practice seeks to control the change process to limit project changes that are non-beneficial to project budget, schedule and quality.

2. **Key Benefits**
   An effective change management program will:
   - Identify change impact prior to implementation.
   - Provide management pre-approval and buy-in, no "bad news late."
   - Permit an orderly incorporation of changes into the project plan.
   - Help to control project cost and schedule excursions.

3. **Influence on Project Value Objectives**
   - Regulatory & Standards Compliance ...... +
   - Capital Cost Reduction .... + +
   - Design & Construction Quality .... +
   - Schedule Reduction .... + +
   - Flexibility for Future Use .... +

4. **Practice History/ Maturity**
   Change management is fundamental to projects. It is as old as contracting.

5. **How Common**
   No project avoids change; well-run projects have a change management process.

6. **Best Circumstances for Application**
   Benefits from this practice can be achieved when one or more of the following circumstances exist:
   - Recent related code changes have occurred.
   - The project requires high levels of regulatory qualification and/or inspection.
   - Project definition is ineffectively established or likely to change.
   - Maintaining a design standard is critical or regulatory approval is constraining.
   - Project team is large and complex.
   - The team is trying to beat a historical project cost benchmark or is market-price-driven.
   - Previous similar projects have suffered from substantial scope creep.
   - The project budget is very tight or the current cost forecast is significantly over budget.

7. **Limitations and Pre-Requisites**
   This practice requires that:
   - A well-defined change procedure be established at the beginning of the project. The procedure should include:
     - Identification (description) of the change.
     - Estimate of baseline cost and schedule.

    - Impact of change on project budget and schedule.
    - Identification of the steps required to implement change.
    - Management approval levels.
    - Persons authorized to approve changes.
- The project team includes resources to estimate the cost and schedule impact of proposed changes throughout the course of the project.

8. Linkage with DE

Control of change will help keep projects from missing cost, quality, and schedule goals and help to maintain an orderly flow of project activities. This practice will help to instill an attitude on the project team that changes should benefit the project in some way, and that way should be clearly understood before making it.

9. **References**

- Allen, W. and Ibbs, C. (1995) "Quantitative Impacts of Project Change", *SD-108*, Construction Industry Institute, Austin, TX.
- CII (1994) "Quantitative Effects of Project Change", *RS 43-2*, Construction Industry Institute, Austin, TX.
- CII (2000) "Quantifying the Cumulative Impact of Change Orders for Electrical and Mechanical Contractors", *RS 158-1*, Construction Industry Institute, Austin, TX.
- Hanna, A. (2001), "Quantifying the Cumulative Impact of Change Orders for Electrical and Mechanical Contractors", *RR 158-11*, Construction Industry Institute, Austin, TX.
- Hester, W.; Kuprenas, J; and Chang, T. (1991), "Construction Changes and Change Orders: Their Magnitude and Impact", *SD-66*, Construction Industry Institute, Austin, TX.

6. Design Productivity Tracking

1. Practice Objectives

Establishing industry common design productivity metrics than can be used to measure current productivity and historical trends. Allows assessment of impacts of design efficiency improvements and projection of design effort and costs for future projects.

2. Key Benefits

Establishing metrics, measuring performance against them and tracking trends over time will indicate areas needing improvement and can help identify effective corrective approaches. Behaviors are strongly influenced by the metrics set so productivity improvements can be realized over time if the proper metrics are established.

3. **Influence on Project Value Objectives**
   - Capital Cost Reduction .... +
   - Schedule Reduction .... +

4. **Practice History/ Maturity**
   This practice is primarily practiced among only the larger and more technically advanced firms. Level of sophistication and rigor of application varies widely. CII pub.156-1 argues for support of this practice. CII is currently tracking design productivity metrics within its Benchmarking and Metrics initiative.

5. **How Common**
   Not widely practiced in detail due to difficulty of establishing meaningful metrics, cost of measurement and data interpretation, and lengthy calendar time required to ascertain trends.

6. **Best Circumstances for Application**
   Benefits from this practice are leveraged when one or more of the following circumstances exist:
   - The team is trying to beat a historical design performance benchmark.
   - An incentive or compensation is based on design productivity.
   - Owner desires assurance of design progress.
   - Project size/effort is large.

   Success is more likely if the data is readily available and the database is easily updated and maintained. Clear, concise reporting of the results and conclusions is necessary to provide maximum value to the organization.

7. **Limitations and Pre-Requisites**
   Practice requires a planned, concerted effort to develop metrics, measurement procedures, database and reporting tools. Also requires investment for the gathering of measurements, data assessment and reporting on a regular basis. A period of years is usually required to show trends. The parameters and measures collected should be consistent from one project to another and typically accepted within the applicable industry. Numerous factors can affect productivity and it is difficult to isolate specific cause and effect relationships. Implementation requires special expertise.

8. **Linkage with DE**
   Practice can identify impacts of other design effectiveness improvements and quantitatively demonstrate that efficiency is improving. Improving the

productivity of detailed design engineering is a critical step in improving the overall effectiveness of capital projects.

9. References

- Chang, L.; Georgy, M.; and Zhang, L. (2001) "Engineering Productivity Measurement", *RR 156-11*, Construction Industry Institute, Austin, TX.
- CII (1990), "Productivity Measurement: An Introduction", *RS 2-3*, Construction Industry Institute, Austin, TX
- CII (2001) "Engineering Productivity Measurement", *RS 156-1*, Construction Industry Institute, Austin, TX.
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- Walsh, K.; Hershauer, J.; and Wacker, J. (2004), "Engineering Productivity Measurements II", *RR 192-11*, Construction Industry Institute, Austin, TX.

7. 3D, 4D & XD CAD

1. Practice Objectives

Practice is sometimes called model based engineering. The practice moves design from a traditional two-dimensional (2D) plans to 3D, object based designs that can be used for constructability analysis (typically through 3D plus schedule or 4D) analysis. XD refers to the inclusion of other engineering components such as cost, materials properties, etc. Objectives include improved design and construction performance as well as operating efficiencies through visualization, model checking, and stakeholder involvement.

2. Key Benefits

Benefits include spatial conflict avoidance and constructability and operational assessment, schedule simulation and optimization, automated quantity take-offs, integrated cost estimating and trending, exchange of fabrication information, integration with procurement systems, design and data integrity reduces risk and rework in the field. Owners can benefit from use of the design models to support operations and maintenance. The practice accelerates decision making in design and design planning. Practice does allow for some scope increase and optimization but leads to overall more effective project delivery.

3. Influence on Project Value Objectives

- O&M Safety .... +
- Construction Safety .... +
- O&M Efficiency .... +
- Product/Plant/Service Quality .... +

- Design & Construction Quality .... + +
- Schedule Reduction .... +

4. **Practice History/ Maturity**
   3D design is prevalent among leading EPCs for detailed and complex projects. 3D modeling is becoming more common place in industry at large but many of AE design firms still use 2D. 4D has a niche among leading constructors. XD is immature but information standards for plant and building (BIM-Building Information Modeling) are emerging. A very small percentage of design projects use XD although it is growing. The largest benefit of XD approach has typically been realized in design build jobs. Many government agencies and services (CoE, GSA, USCG, US Army, Navy, US Air Force, etc) are beginning to require BIM on their new contracts.

5. **How Common**
   Practiced is used by more technologically advanced AE and EPC firms as a standard operating procedure, although highest levels of integration is still an evolving practice. The use of 3D/4D analysis is increasingly being performed on projects across the industry, although designers, owners, and contractors are still learning how to best deploy the technologies.

6. **Best Circumstances for Application**
   Benefits from this practice are leveraged when one or more of the following circumstances exist:
   - Visual simulation can significantly enhance or optimize accessibility, sequencing, layout/configuration, or user preferences; or physical interference detection will be very beneficial; or automated material take-offs are desirable.
   - Communication of design configuration with owner/user stakeholders.
   - Design can benefit from a scenario simulation approach.
   - Owner is committed to life-cycle cost reduction analysis.

7. **Limitations and Pre-Requisites**
   There is an initial cost due to first time learning curve, but once proficiency is attained, productivity increases are observed. Staff typically needs additional training in use of the tools. Optimal deployment typical involves changes in work practices, particularly when sharing information across organizations. Emerging information standards can hamper effective data exchange.

8. **Linkage with DE**
   This design practice can result in a more cost-effective design product due to effective change management, and reductions in capital and life cycle costs. It is particularly valuable for EPC and EPC-operate projects.

9. **References**

- CII (1995) "3D CAD Link", *RS 106-1*, Construction Industry Institute, Austin, TX
- CII (2001), "3D CAD and FIAPP: Three-Dimensional Computer Models and the Fully Integrated and Automated Project Process", *RS 152-1,* Construction Industry Institute, Austin, TX
- FIATECH Website www.fiatech.org [accessed 07/02/2007]
- Langford, D. and Retik, A. (2001). *Computer Integrated Planning and Design*, Thomas Telford Publishing, London.

8. Design Automation & Software

1. **Practice Objectives**
Uses leading edge computer applications including expert and knowledge-based systems to reduce the effort and cost needed to develop designs. Effective implementation also improves quality and consistency and enhances ability to share work in remote locations (distributed design or off shoring). Practice can employ vendor purchased or internally developed packages.

2. **Key Benefits**
Benefits include work sharing and collaboration with remote locations, reuse of information, improved time to market, and improved quality.

3. **Influence on Project Value Objectives**
   - Regulatory & Standards Compliance ...... +
   - Product/Plant/Service Quality .... +
   - Design & Construction Quality .... + +

4. **Practice History/ Maturity**
Practice is in early stages of development. The number of applications and scope and power of solutions is increasing rapidly. The first generation solutions were point solutions and may have been developed internally. Next generation products focus on interoperability and are developed commercially with configuration by customer.

5. **How Common**
Penetration and acceptance varies widely by market. Practice is very extensive among EPC leaders and owners in industrial markets. Not as extensive among smaller firms in the AE marketplace. However, even the smallest firms are using some level of design automation technology. Practice includes engineering calculations and simulation, modeling, and integrated database for design, procurement, construction and O&M.

6. **Best Circumstances for Application**
   Benefits from this practice are leveraged when one or more of the following circumstances exist:
   - Project team is large and complex.
   - Design can benefit from a scenario simulation approach.
   - Multi-system interoperability offers higher levels of optimization.
   - There is benefit from early electronic design approach, or manual design approach is time consuming.
   - Design software systems offer higher levels of optimization.
   - Integrated suppliers can benefit from exchange of digital design data.
   - Project has highly complex design geometry.

7. **Limitations and Pre-Requisites**
   Interoperability from suite of programs is best otherwise information exchange may be an issue. Liability of program with errors and black box effect is an issue.

8. **Linkage with DE**
   Practice provides a design delivery platform that is highly competitive, facilitates comparison of design alternatives and provides high value to the customer.

9. **References**

   - Autodesk: AutoCAD Civil 3D http://www.autodesk.com/civil3d [accessed 07/02/2007]
   - Civil Engineering Software List http://www.tenlinks.com/engineering/civil/software.htm [accessed 07/02/2007]
   - Langford, D. and Retik, A. (2001). Computer Integrated Planning and Design, Thomas Telford Publishing, London.
   - Transoft Solutions http://www.transoftsolutions.com/ [accessed 07/02/2007]

9. Virtual Teams

1. **Practice Objectives**
   Draw upon the best available as well as most cost-effective technical resources regardless of geographic location to produce designs of the highest value and quality.
2. **Key Benefits**
   Avoids the need to co-locate design team. Many people prefer not to relocate (temporarily of permanently); practice allows global utilization of such resources. This approach also reduces the labor cost and expenses associated with travel and

team housing. Allows use of people in areas of the world where they are in plentiful supply to execute projects in locations where people with the necessary expertise and competence are unavailable, limited or more expensive. It can reduce overall design costs. Practice enhances the ability to acquire sufficient resources to meet demanding deadlines that may not otherwise be achieved.

3. Influence on Project Value Objectives

- Security .... –
- Capital Cost Reduction .... +
- Schedule Reduction .... +

4. Practice History/ Maturity

Practice has become common fairly recently; development and use of computer-based design tools has promoted virtual teaming. The routine availability of global, real-time communications has made this practice a common reality.

5. How Common

Practice is becoming more common among industry leaders. Limited supply of key technical resources in the U. S. and the "war for talent" are key drivers.

6. Best Circumstances for Application

Benefits from this practice are leveraged when one or more of the following circumstances exist:

- Best or most economical technical resources (i.e. specialists) are geographically separated.
- Team benefits from project-centric information exchange system.
- Non-virtual team collaboration costs are too high.

Also helpful for implementation: Effective chartering of the entire team to ensure that each member endorses the team's mission, objectives, direction, values and behaviors.

7. Limitations and Pre-Requisites

Barriers include widely varying time zone differences, use of second languages, and different national and corporate cultures and values. Care must be taken to ensure that the team members feel they are part of a greater whole rather than individual performers. Regulatory constraints are sometimes present (e.g., State professional engineering regulations) and owner dictated restrictions. For highly complex projects that require significant coordination, virtual teams may face challenges in achieving the same level of communication and coordination as a co-located team. If the design team members are geographically dispersed, it becomes more of a challenge to ensure the work of the disciplines is coordinated for interferences, etc. This is particularly true for projects that involve rehabilitation of existing facilities. Multiple forms of instantaneous, real-time communication, collaboration and coordination are necessary.

8. **Linkage with DE**
This design practice allows inclusion/participation of design resources that might not otherwise be available. It can be especially useful with regard to specialized, highly technical requirements.

9. **References**

- Chinowsky, P. and Rojas, E. (2002), "Virtual Teams: A Guide to Successful Implementation", *RR 170-11,* Construction Industry Institute, Austin, TX.

10. Technology Tracking & Selection

1. **Practice Objectives**
Technology selection seeks to systematically optimize selection of technologies not currently used by an owner organization that can improve facility performance. The practice focuses is on staying abreast of emerging construction technologies and building products, which may involve technology performance benchmarking.

2. **Key Benefits**
Improve facility performance along one or more dimensions: capital and O&M cost, maintenance, product quality, capacity, etc. The use of new technologies and products may reduce first costs (construction material and labor costs), as well as operational costs (building energy use savings, maintenance and labor costs). This practice can offer strategic advantage.

3. **Influence on Project Value Objectives**
- Security .... +
- O&M Safety .... +
- Construction Safety .... +
- Regulatory & Standards Compliance .... +
- Capital Cost Reduction .... +
- O&M Efficiency .... +
- Product/Plant/Service Quality .... +
- Design & Construction Quality .... +
- Schedule Reduction .... +
- Environmental Stewardship .... +
- Flexibility for Future Use .... +

4. **Practice History/ Maturity**
   This practice is very mature. It is essential to technology-driven companies. In the industrial sector this is a Value Improving Process endorsed by IPA.

5. **How Common**
   Applied by IPA clients, and also used by EPC's and EA's. Most designers likely use informal processes to identify new technologies.

6. **Best Circumstances for Application**
   Benefits from this practice are leveraged when one or more of the following circumstances exist:
   - Owner is committed to life-cycle cost reduction analysis.
   - New related technologies are emerging; best available technology may have changed.
   - Technology selection circumstances have changed (i.e. market, prices, regulations, etc.).

7. **Limitations and Pre-Requisites**
   Practice is most commonly applied by owners for new process technologies. In the building construction industry, owner organizations are often reluctant to assume the risks involved in the use of products/technologies that haven't been proven. Also, new products are often proprietary in the early stages, and therefore economies inherent in a competitive environment are not available. Early adopters may have a significant advantage over their competitors. Implementation requires special expertise.

8. **Linkage with DE**
   Practice supports effective design by forcing focus on technologies external to the organization. Focusing on emerging technologies encourages new approaches and therefore opportunity for improvement.

9. **References**

   - Clemen, R. and Reilly, T. (2001). *Making Hard Decisions*, Duxbury, Pacific Grove, CA;
   - Department of Energy's Industrial Technologies Program http://www.eere.energy.gov/industry [accessed 07/02/2007];
   - Emerging Construction Technologies http://www.ecn.purdue.edu/ECT/Civil/civil.htm [accessed 07/02/2007]
   - FIATECH http://www.fiatech.org [accessed 07/02/2007]
   - IPA http://www.ipaglobal.com/index.asp [accessed 07/02/2007]

OPPORTUNITY CAPTURE/DESIGN FOR X

11. Design for Constructability

1. **Practice Objectives**
   The primary objective is to incorporate construction knowledge and experience into the design and procurement of a project.
2. **Key Benefits**
   Constructability input can positively impact project performance in several value objectives: safety, quality, schedule and cost. Providing the resources and establishing the processes to obtain and incorporate constructability input in a timely manner maximizes the influence on the project objectives while avoiding costly rework and schedule delays when key constructability input is received at the end of the design phase.

3. **Influence on Project Value Objectives**
   - Construction Safety .... + +
   - Regulatory & Standards Compliance ...... +
   - Capital Cost Reduction .... + +
   - Design & Construction Quality .... + +
   - Schedule Reduction .... + +

4. **Practice History/ Maturity**
   Constructability has been practiced formally for approximately 20 years. The impetus for pursuing the practice arose out of Business Roundtable studies entitled the Construction Industry Cost Effectiveness Project. The Business Roundtable, comprised of owners, academics, engineers and contractors, issued a summary report called "More Construction for the Money." This study recognized a need to inject construction experience into the planning, design and engineering phases of projects in order to improve projects' effectiveness relative to cost and schedule. Through the 1980's and 1990's, the practice became more widely used in industry and several studies were performed by CII and other research institutions. CII published various studies, including "Constructability: A Primer" in 1986 and "Guidelines for Implementing a Constructability Program" in 1987. Companies have developed constructability programs that have evolved and matured into different formats and execution styles. Recognizing the demonstrated benefits of implementing a constructability program, owner organizations have endorsed and in some cases require it on their projects.

5. **How Common**
Constructability programs are currently nearly universal on large industrial projects. Many owners expect or require reviews to be performed by EPC contractors. In government projects, constructability input is frequently a part of Value Engineering exercises. Where the execution strategy entails fragmented contracting, some owners will hire a construction manager or a general contractor to perform constructability reviews at a certain percent design complete.

6. **Best Circumstances for Application**
Benefits from this practice are leveraged when one or more of the following circumstances exist:
    - Design team has limited experience with related technologies.
    - Project has highly complex design geometry.
    - New related technologies are emerging; best available technology may have changed.
    - Technology selection circumstances have changed (i.e. market, prices, regulations, etc.).
    - Accessibility-related challenges within site.
    - Shortage of skilled labor.
    - Project involves repetitive shop work tasks.
    - Harsh site climate or seasonal effects on construction or inhospitable working environment.
    - Project is extremely schedule-driven.
    - Critical, major materials are in short supply and/or are difficult to transport.

7. **Limitations and Pre-Requisites**
The worst circumstances for application are on smaller design-bid-build contracts where the constructor has very limited ability to influence the design. Pre-requisites include commitment from the owner, company management, and project management, engineering/design receptiveness, and a source of construction knowledge and expertise.

8. **Linkage with DE**
The practice of constructability improves design effectiveness with respect to project safety, quality, schedule and cost. Constructability is one of the seven most significant contributors to design effectiveness according to the CII Design Effectiveness study. Most design engineers recognize that they are tasked with maximizing constructability as one of their responsibilities. Enhancement of constructability in design and procurement enhances overall project performance.

9. **References**

- Choi, Y. (2004). *Principles of Applied Civil Engineering Design, American Society of Civil Engineers,* Reston, Virginia

- CII (1986), “Constructability: A Primer”, *RS 3-1,* Construction Industry Institute, Austin, TX
- CII (1987) “Guidelines for Implementing a Constructability Program”, *RS3-2*, Construction Industry Institute, Austin, TX.
- O’Connor, J. and Hugo, F. (1991) “Improving Highway Specifications for Constructability”, *Journal of Construction Engineering and Management*, Vol. 117, No. 2, June 1991, pp. 242-258.
- O’Connor, J. and Miller, S. (1993), “Constructability: Program Assessment and Barriers to Implementation”, *SD-85*, Construction Industry Institute, Austin, TX
- Russell, J.; Radtke, M.; and Gugel, J. (1992), “Project-Level Model and Approaches to Implement Constructability”, *SD-82,* Construction Industry Institute, Austin, TX
- Russell, J.; Radtke, M.; and Gugel, J. (1992), “Benefits and Costs of Constructability: Four Case Studies”, *SD-83*, Construction Industry Institute, Austin, TX
- Tatum, C.; Vanegas, J.; and Williams J. (1986), “Constructability Improvement During Conceptual Planning”, *SD-4,* Construction Industry Institute, Austin, TX

12. Design for Construction Automation

1. **Practice Objectives**
   Design projects so that efficient, advanced construction technologies can be used.

2. **Key Benefits**
   Increased construction productivity and safety, and often quality are realized. Designing for construction automation facilitates using a process, tools and or equipment that can perform work in an automated or semi-automated fashion. Through this automation, work can be performed with fewer job hours, in a shorter duration and with higher quality. Practice helps to maximize the advantage and benefit from use of construction automation, such as: Field productivity gains, reduce impact of shortage of skilled labor, avoidance of safety hazards, and improved quality (such as automated welds).

3. **Influence on Project Value Objectives**
   - Construction Safety .... + +
   - Capital Cost Reduction .... +
   - Design & Construction Quality .... +
   - Schedule Reduction .... +

4. **Practice History/ Maturity**
   Practiced among only the most technically advanced; CII pub. 183-1 argues for support of this practice. Construction automation is practiced more extensively in

Japan due to cultural and societal drivers. This practice may be considered as a sub-set of constructability practice.

5. **How Common**

Currently not very common – but could/should become more common as the number and power of construction automation devices increases.

6. **Best Circumstances for Application**

Benefits from this practice are leveraged when one or more of the following circumstances exist:

- Use of repetitive or high volume elements or components.
- Shortage of skilled labor.
- Project involves repetitive shop work tasks.
- Automated design data can facilitate or drive automated processes.
- Requirement for consistent quality (e.g. nuclear steam pipe welding).
- Projects which have life-critical construction safety exposures that designers can address (i.e. elevated work, confined spaces, combustible/explosive materials, heavy lifting, deep excavations and excavations around existing utilities, sources of high-energy, etc.).

7. **Limitations and Pre-Requisites**

Specific construction technologies need to be considered during the design phase. Currently the number of available automated construction devices is limited. Processes where judgment is needed are not suitable. Fully automated is much more difficult than semi-automated. Prerequisites include a technology champion on the project or in the company, a management sponsor, a receptive owner and a commitment to invest seed time and money to get the implementation started. Moreover, implementation requires special expertise.

8. **Linkage with DE**

Practice makes design product more responsive to the needs of construction. In some cases, the entire design must be tailored to suit a particular construction automation technology. In most cases, a subset of the design is created with the construction automation tool requirements incorporated.

9. **References**

- CII (2003), "Design Practices to Facilitate Construction Automation", *RS 183-1*, Construction Industry Institute, Austin, TX
- Gambatese, J. and Dunston, P. (2003), "Design Practices to Facilitate Construction Automation", *RR 183-11*, Construction Industry Institute, Austin, TX

13. Design for Construction Safety

1. **Practice Objectives**
   Objective is to prevent construction injury ordeath, specifically by integrating safety measures in final product design.

2. **Key Benefits**
   The key benefit to designing for construction safety is that injuries to workers are prevented. Secondary benefits of construction safety include lower accident costs, reduced insurance rates, improved productivity and better morale. Safety performance statistics are often considered by project owners and construction managers as the first set of evaluation criteria for bid qualification and/or contract award.

3. **Influence on Project Value Objectives**
   - O&M Safety .... +
   - Construction Safety .... + +
   - Regulatory & Standards Compliance ..... + +
   - Capital Cost Reduction .... +
   - Design & Construction Quality .... +
   - Schedule Reduction .... +

4. **Practice History/ Maturity**
   Procedure originated in aerospace, nuclear, chemical, offshore, rail, and other industrial practices. Petrochemical companies have developed handbooks in the early 1990s that address safety in design, including the common practices that are to be implemented. Practice is sometimes part of a broader constructability effort that often contains a large PPMOF element. Practice needs further enhancement and more effective tools.

5. **How Common**
   Practice is very common in large and medium size companies in the US, and in highly developed nations. It should be practiced in developing nations.

6. **Best Circumstances for Application**
   All projects should be designed for construction safety. Benefits from this practice are leveraged when one or more of the following circumstances exist:
   - Shortage of skilled labor.

- Harsh site climate or seasonal effects on construction or inhospitable working environment.
- Requirement for consistent quality (e.g. nuclear steam pipe welding).
- Projects which have life-critical construction safety exposures that designers can address (i.e. elevated work, confined spaces, combustible/explosive materials, heavy lifting, deep excavations and excavations around existing utilities, sources of high-energy, etc.).

7. **Limitations and Pre-Requisites**
This practice can be used on any project. It is notable that designers of supplied equipment as well as plant / building designers (integrators) contribute to design for construction safety. Prerequisites include a source of expertise for construction safety tools/methods/technologies and a project commitment to maximize construction safety.

8. **Linkage with DE**
A safe design promotes our value to protect workers from injury and illness. For this reason, the practice is the most important one for many companies & projects.

9. **References**

   - CII (2003), "The Owner's Role in Construction Safety", *RS 190-1*, Construction Industry Institute, Austin, TX
   - CII (1996), "Design for Construction Safety Toolbox", *IR 101-2*, Construction Industry Institute, Austin, TX
   - Hinze, J. and Huang, X. (2003), "The Owner's Role in Construction Safety", *RR 190-11*, Construction Industry Institute, Austin, TX
   - Liska, R. (1993), "Construction Safety Self-Assessment Process", *SD-88*, Construction Industry Institute, Austin, TX
   - MacCollum, D. (1995). *Construction Safety Planning*, John Wiley and Sons, Inc., New York.

14. Design to Cost

1. **Practice Objectives**
Achieve a project design that correlates with an established budget. This is normally accomplished by setting and controlling design variables, such as project scope, quality and schedule.

2. **Key Benefits**
Practice seeks to achieve a total project cost that meets budget objectives. BThe project team is forced to carefully consider, prioritize and cost estimate all project variables. Effectively accomplished, this can lead to a very efficient design solution, meeting the project objectives.

3. Influence on Project Value Objectives

- Capital Cost Reduction .... + +
- O&M Efficiency .... –
- Schedule Reduction .... –
- Flexibility for Future Use .... –

4. Practice History/ Maturity

5. How Common

80-90% of projects are design to cost (exception: schedule driven projects).

6. Best Circumstances for Application

Benefits from this practice can be achieved when one or more of the following circumstances exist:

- The team is trying to beat a historical project cost benchmark or is market-price-driven.
- Related market cost pressures are ever increasing.

7. Limitations and Pre-Requisites

This practice requires that a format be available or established at the beginning of the project to subdivide the project into discrete design elements that will be subject to cost evaluation. Also, the project team must include resources to estimate the cost of the design elements throughout the course of the project. The success of this design practice requires periodic, accurate cost estimates and rigorous change control throughout the design process. Some risk transfer to the owner may exist. Caution must be exercised so as not to over promise. Use cost indices. Complications exist from Sarbanes-Oxley law.

8. Linkage with DE

Practiced successfully, design to cost will accomplish primary project objectives and may engender creative and responsive designs.

9. References

- Michaels, J. and Wood, W.(1989), *Design to Cost,* John Wiley, New York, NY
- Riggs, L. (1986) “Cost and Schedule Control in Industrial Construction”, *SD-24*, Construction Industry Institute, Austin, TX

15. Design for Energy Efficiency

1. **Practice Objectives**
   Increase the overall energy efficiency of facilities and their mechanical and electrical support systems by special consideration during the project design phase.

2. **Key Benefits**
   The primary advantage is the reduction in facility operating costs and support for sustainability efforts. An energy efficient design for buildings and their support systems will provide the lowest total cost of ownership (TCO) over the life of the facility.

3. **Influence on Project Value Objectives**
   - Regulatory & Standards Compliance ...... +
   - Capital Cost Reduction .... –
   - O&M Efficiency .... + +
   - Environmental Stewardship .... + +

4. **Practice History/ Maturity**
   Practice includes many techniques that are discipline specific. No specifically organized, project-wide practices – an emerging area. Recent design focus areas also relate to LEED (Leadership in Energy and Environmental Design) and related green building standards. An exception is life cycle costing (LCC), which is an established cost/benefit methodology for comparing specific alternatives.

5. **How Common**
   With increasing energy costs worldwide, focus on best design practices and TCO is likely to become more common. LCC analysis is now required on many government facilities for major systems and increasingly endorsed by the corporate sector. LEED or other "green" certification is becoming more common.

6. **Best Circumstances for Application**
   Benefits from this practice are leveraged when one or more of the following circumstances exist:
   - Owner is committed to life-cycle cost reduction analysis.
   - Owner requirement for sustainability or operational energy savings.
   - Flexibility in facility siting, orientation, and envelope.
   - Energy supply is limited
   - Project is a federal facility or located in states that have mandated LCC analysis.

7. **Limitations/Applicability**
Primarily focuses on cost savings during operations. On sites where pre-negotiated energy costs are not possible, TCO calculations should consider projected annual increases for the cost of electrical energy, natural gas and fuel oil.

8. **Linkage with DE**
Practice(s) closely supports effective design for this dimension. Factory system design and operational standards should, at the minimum, comply with DE and Environmental standards. Where DE or Environmental Standards conflict, the most stringent standard should be adhered to.

9. **References**
   - ASHRAE: www.ashrae.org/moldsatellitebroadcast [accessed 07/02/2007]
     Design Manuals & Standard 90.1-2004 which dictates minimum performance standards.
     - ASHRAE Fundementals Guide (2005)
     - ASHRAE Refrigeration Guide (2006)
     - ASHRAE HVAC Systems & Equipment Guide (2004)
     - ASHRAE HVAC Applications (2003)
     - ASHRAE Publication 189, 2007
   - ASME: www.asme.org/ [accessed 07/02/2007]
   - DOE: www.eere.energy.gov/buildings/info/components/hvac [accessed 07/02/2007]
   - Fuller, S. and Petersen, S. (1996) "Life-Cycle Costing Manual for the Federal Energy Management Program", NIST Handbook 135, Government Printing Office.
   - LEED: www.usgbc.org [accessed 07/02/2007]
   - Modeling Software Efficient MEP systems
     - DOE 2 http://www.doe2.com/ [accessed 07/02/2007]
     - Energy Plus http://www.eere.energy.gov/buildings/energyplus/index.html [accessed 07/02/2007]
     - eQuest v3 http://www.doe2.com/equest/ [accessed 07/02/2007]
     - Trace 700 http://www.trane.com/commercial/software [accessed 07/02/2007]

16. Design for Expandability

1. **Practice Objectives**
Facilitate future expansion through current facility design approaches. Reduce future cost of construction, impacts to operations, and construction duration with current strategic investment.

2. **Key Benefits**
   The primary advantage is reduction in future facility expansion cost and operations impact by investing more in current facility systems. If future expansion is highly likely, longer-term life-cycle costs can be reduced.

3. **Influence on Project Value Objectives**
   - Capital Cost Reduction .... –
   - Schedule Reduction .... –
   - Flexibility for Future Use ....+ +

4. **Practice History/ Maturity**
   Practice includes intelligent planning techniques that are mostly discipline-specific. This practice is often a neglected opportunity due to current capital cost pressures.

5. **How Common**
   Frequency of application is dependent upon knowledge of future expansion. Application to design of infrastructure and utility systems has been particularly important – and beneficial.

6. **Best Circumstances for Application**
   Benefits from this practice are leveraged when one or more of the following project characteristics are present:
   - Project has a high cost or high consequences of downtime (i.e. life safety, revenue, system service, etc.).
   - Owner is committed to life-cycle cost reduction analysis.
   - Marginal cost of added capacity is high.
   - Accessibility-related challenges exist within site.
   - Facility is located in an environmentally-sensitive area.
   - Facility undergoes frequent reconfiguration.

7. **Limitations/Applicability**
   Practice can be difficult to apply on congested sites or on projects that are capital cost-constrained. The practice is more applicable for long-life facilities with predictable needs for and approaches to facility expansion.

8. **Linkage with DE**
   Practice closely supports effective design when elements of future expansion are predictable.

10. References

- EPA, ISO 14001 Document http://www.epa.gov/owm/iso14001/wm046200.htm [accessed 07/02/2007]
- IEEE http://www.ieee.org [accessed 07/02/2007]

17. Design for Maintainability

1. Practice Objectives

Design for the needs of maintenance personnel and understand how the maintenance operations will be performed. Consider design features that allow maintenance operations to be performed in a safe and efficient manner. Provide adequate space, access platforms, and special design features such as lifting devices to facilitate maintenance operations. Design to minimize disruption to production operations during maintenance operations.

2. Key Benefits

Reduced time and cost to perform maintenance operations, increased safety of personnel, and reduced disruption to production operations.

3. Influence on Project Value Objectives

- O&M Safety .... + +
- Capital Cost Reduction .... –
- O&M Efficiency .... + +
- Product/Plant/Service Quality .... +

4. Practice History/ Maturity

Equipment arrangements and design layouts has always included considerations for maintenance from a general space allocation perspective. Larger projects have incorporated maintenance personnel into project teams during early Front End Loading (FEL). Lack of maintenance personnel input contributes to additional costs. These added costs usually occur after mechanical completion of the project.

5. How Common

Practice is commonly used on larger projects due to economic considerations.

6. Best Circumstances for Application

Benefits from this practice are leveraged when one or more of the following circumstances exist:

- Projects with a high cost or high consequences of downtime (i.e. life safety, revenue, system service, etc.).
- Projects that involve labor-intensive maintenance operations.

- Projects with many equipment options that vary in durability and maintenance requirements.
- Projects that can benefit from predictive maintenance technologies.
- Projects that involve bulky, heavy, or hazardous operations and/or maintenance.

7. Limitations and Pre-Requisites
Practice requires initial cost and input from maintenance personnel during design.

8. Linkage with DE
Practice makes design product more effective for performance of maintenance operations, reduces maintenance personnel to hazards, and can result in minimization of plant shutdown requirements.

9. References

- CII (1999) "Design for Maintainability: Improving Project Return on Investment", *RS 142-1,* Construction Industry Institute, Austin, TX
- Russell, J.; Meier, J.; and Moua, B. (1999), "A Model Process for Maintainability Implementation", *RR 142-11*, Construction Industry Institute, Austin, TX
- Russell, J.; Meier, J.; and Moua, B. (1999), "State-of-Practice in Maintainability: Seven Case Studies", *RR 142-12*, Construction Industry Institute, Austin, TX

18. Design for Operational Automation

1. Practice Objectives
To identify and incorporate into the project design appropriate automated operational technology in areas such as:

- Manufacturing, processing and packaging.
- Warehousing, logistics, tracking and distribution.
- Analytical control processes.
- Utility generation facilities.
- Building environmental and safety systems.
- Communications and security.
- Transportation systems (people and freight).
- Robotics.

2. **Key Benefits**
   The use of automated controls or automated equipment can improve operational:
   - Safety.
   - Efficiency.
   - Consistency.
   - Material tracking.
   - Operational modeling/forecasting.
   - Line yield.

3. **Influence on Project Value Objectives**
   - Security .... +
   - O&M Safety .... + +
   - Capital Cost Reduction .... –
   - O&M Efficiency .... + +
   - Product/Plant/Service Quality .... + +
   - Schedule Reduction .... –
   - Environmental Stewardship .... +

4. **Practice History/ Maturity**
   Practice is currently emerging in industry. Warehousing is highly mature, followed by some high volume manufacturing.

5. **How Common**
   It is increasingly common, even in the building and infrastructure sectors.

6. **Best Circumstances for Application**
   Benefits from this practice can be achieved when one or more of the following circumstances exist:
   - Project is being executed in a region having a shortage of required skilled process operators, but adequate technicians to operate and maintain an automated system.
   - Manual operation requires significant repetitive steps that may lead to ergonomic issues with personnel.
   - Mature, reliable automated systems exist for the desired operation with minimal customization required.
   - Manual operation cannot achieve the desired operational performance.
   - Operational loads are too heavy for manual operation.
   - Operation is conducted in hazardous environments or environments non-conducive to manual operation (e.g. low light).
   - Operation requires high placement precision.
   - Real time tracking of the movement of items in a process is required.

7. **Limitations and Pre-Requisites**
   Several factors must be carefully evaluated prior to recommending and proceeding with an automated approach to an operation:
   - Cost/benefit (capital cost and cost of ownership).
   - System reliability (hardware and software).
   - Owner/regional capabilities for operation and maintenance.
   - Ability to integrate with (or replace) other operational systems.

8. **Linkage with DE**
   Automated systems can greatly enhance the effectiveness of the design and increase the number of feasible design options, but may require a greater design effort both in hardware and software.

9. **References**

   - Automated Materials Handling Society www.asrs.org [accessed 07/02/2007]
   - Control Engineering - www.controleng.com [accessed 07/02/2007]
   - IEEE Robotics and Automation Society - www.ieee-ras.org [accessed 07/02/2007]
   - Instrumentation, Systems, and Automation Society (links to ISA & ANSI stds) - www.isa.org [accessed 07/02/2007]
   - International Federation of Automatic Controls (IFAC) - www.ifac-control.org [accessed 07/02/2007]

19. Design for Operational Safety

1. **Practice Objectives**
   Incorporate design features to support operational safety. Discuss the needs of operations personnel and understand how the facility will be operated. Consider design features that allow production operations to be performed in a safe and efficient manner.

2. **Key Benefits**
   Practice provides a safer work environment for day-to-day operations and reduced opportunity for operational accidents. To achieve these benefits, the design should include consideration of access around equipment, location of valves, egress, safety showers, separation distances, egress travel distances, and ergonomics for operating equipment.

3. **Influence on Project Value Objectives**
   - Security .... +
   - O&M Safety .... + +
   - Regulatory & Standards Compliance ...... + +
   - Capital Cost Reduction .... –
   - O&M Efficiency .... +
   - Product/Plant/Service Quality .... +

4. **Practice History/ Maturity**
   This practice is considered by OSHA, fire and building codes, and company specific policies. All facilities are designed to be in accordance with fire and building codes and OSHA. However, specific company design standards vary widely. Larger projects have incorporated operations personnel into project teams during early project development. Lack of operations input can contribute to additional operating costs and potential safety hazards.

5. **How Common**
   All projects follow formal compliance with fire and building codes and OSHA. Extension of use to meet the specialized needs of operations personnel has been exercised on a more limited basis.

6. **Best Circumstances for Application**
   All projects need to be designed for operational safety. Benefits from this practice are leveraged when one or more of the following circumstances exist:
   - Projects with a high cost or high consequences of downtime (i.e. life safety, revenue, system service, etc.).
   - Harsh site climate or seasonal effects on construction or inhospitable working environment.
   - Requirement for consistent quality (e.g., nuclear steam pipe welding).
   - Projects that involve bulky, heavy, or hazardous operations and/or maintenance.

7. **Limitations and Pre-Requisites**
   Practice requires initial cost and availability of operations personnel for additional benefits.

8. **Linkage with DE**
   Practice is a basic element of DE for fire and building code and OSHA compliance.

9. References

- Levitt, R. and Samelson, N.(1993) *Construction Safety Management*, John Wiley and Sons, New York, NY.
- OSHA http://www.osha.gov [accessed 07/02/2007]
- Gherardi, S.; Nicolini, D.; and Odella, F. (1998) "What Do You Mean By Safety? Conflicting Perspectives on Accident Causation and Safety Management in a Construction Firm", *Journal of Contingencies and Crisis Management* 6 (4), 202–213.
- Tam, C.; Tong, T.; Chiu, J.; and Fung, I. (2002) "Non-Structural Fuzzy Decision Support System for Evaluation of Construction Safety Management System", *International Journal of Project Management*, 20 (4), 303-313
- Wilson, J. and Koehn, E. (2000), "Safety Management: Problems Encountered and Recommended Solutions" *Journal of Construction Engineering and Management*, 126(1), pp. 77-79

20. Design for People

1. Practice Objectives

The objective of this practice is to design for the safety, comfort, enjoyment and productivity of people living and working within facilities. In some manufacturing environments, achieving these objectives can be difficult, but is no less important.

2. Key Benefits

Practice addresses ergonomics, adequate space, convenience of access to supporting areas, temperature control, fresh air and ventilation, mold avoidance, appropriate lighting, accessibility for the disabled, and aesthetic considerations. In turn, these conditions support workforce productivity and well being.

3. Influence on Project Value Objectives

- Security .... +
- O&M Safety .... + +
- Regulatory & Standards Compliance ...... +
- Capital Cost Reduction .... –
- O&M Efficiency .... +
- Product/Plant/Service Quality .... +
- Environmental Stewardship .... +

4. Practice History/ Maturity

Practice is very mature. In the early 1900's, a system of building standards and regulations (also known as life safety or building codes) were initially established and enforced in response to tragic events incurring loss of life to people trapped in buildings during natural or manmade disasters such as fires. Current versions of life safety codes include provisions for egress, ventilation, fire-resistance rated construction, accessibility, lighting, temperature control, structural integrity, etc. Life safety codes are typically understood to provide minimum requirements for the safety and comfort of people. However, higher standards should be strived for to achieve optimal building environments for human habitation. Practice is currently developing with new research, corporate standards, etc.

5. **How Common**

Practice is fundamental to the design of buildings. However, it is frequently overlooked beyond minimal codes.

6. **Best Circumstances for Application**

Benefits from this practice are leveraged when one or more of the following circumstances exist:

- Facility has high occupancies.
- Facility in which aesthetics is important to public perception, sales, or rental potential.
- Facilities that benefit from orientation and way-finding schemes.

7. **Limitations and Pre-Requisites**

This practice requires that the design team have access to, or resources to develop, a definition of the needs of the people occupying the facility. This definition should include:

- Lighting levels, glare concerns.
- Acoustics.
- Visual privacy.
- Ventilation/temperature/humidity.
- Ergonomics.
- Odors, toxicity.
- Accessibility.
- Space and color psychology.
- ESD.

8. **Linkage with DE**

Practice is increasingly integral to design effectiveness as concern for workers is viewed as a strategic priority.

9. **References**

- Rubin, A. and Elder, J. (1980), *Building for People: Behavioral Research Approaches and Directions*, U.S Dept. of Commerce, Washington, D.C.
- Dechiara, J.; Panero, J.; and Zelnik, M. (2001), *Time Saver Standards for Interior Design and Space Planning, 2nd Edition*, McGraw-Hill, New York, NY
- Porter, R. (1982) *Building for People: Occupant Behavior Information for Environmental Design*, S.N, Champaign, IL.

21. Design for PPMOF

1. **Practice Objectives**

Practice aims to reduce construction cost and schedule by using offsite labor and location, reduce manpower peaks, increase parallel work, solve local labor shortages, and facilitate construction in locations with labor constraints, site space constraints, limited transportation access, harsh climates and/or small local populations.

2. **Key Benefits**

PPMOF (prefabrication, preassembly, modularization, and offsite fabrication) removes construction work scope from the project work site and shifts it to a location selected by the project. Shortens schedule at the work site since large pieces are assembled in a shorter period. Usually reduces labor costs per hour by using a low cost labor location for PPMOF. Reduces work in hazardous conditions related to climate, limited daylight, work operations, work at heights, political instability, etc. Lowers peak manpower needs, thereby reducing need to import labor, construct work camp modules, train local work force, utilize lower skilled labor and subcontract work.

3. **Influence on Project Value Objectives**

- Construction Safety .... +
- Capital Cost Reduction .... +
- Design & Construction Quality .... + +
- Schedule Reduction .... + +

4. **Practice History/ Maturity**

PPMOF has been practiced for about 45 years, initially for cold climates with short work seasons (e.g. North Slope Alaska modules). It has been increasing in usage as labor costs have increased and skilled craft availability decreased.

5. **How Common**
   It is very common in large industrial sector projects, especially in remote locations, harsh climates and high labor cost areas. Short schedules and long lead permits also drive practice.

6. **Best Circumstances for Application**
   Benefits from this practice are leveraged when one or more of the following circumstances exist:
   - Shortage of skilled labor.
   - Harsh site climate or seasonal effects on construction or inhospitable working environment.
   - Project is extremely schedule-driven.
   - Projects which have life-critical construction safety exposures that designers can address (i.e. elevated work, confined spaces, combustible/explosive materials, heavy lifting, deep excavations and excavations around existing utilities, sources of high-energy, etc.).
   - High local wage rates at project site.
   - Limited lay-down or pre-fab space at site or excessive work density.
   - Remote site location or limited transportation access.
   - Political instability.
   - Pre-shipment systems integration and testing can be very beneficial.

7. **Limitations and Pre-Requisites**
   Modules and other prefabricated components must be transportable to the project site. Heavy lift equipment (e.g. port and/or ship cranes, cranes on shore, or roll-off heavy haulers must be capable of lifting/transporting the module. Local content contract provisions may preclude all or part of importing PPMOF components into foreign countries. Government projects with Buy American contract clauses may require modularization to be done in the United States. Prerequisites include a facility with scale adequate to justify engaging the team in PPMOF and a bridging mechanism between different project participants or within the project organization that allows a high level of coordination between construction, procurement and engineering groups.

8. **Linkage with DE**
   An effective design on a PPMOF project includes clearly designing modules for off site modularization or prefabrication. Modules must maximize extent of shop and offsite fabrication while meeting limitations of transportation and rigging. For best results, design must be tailored early to support PPMOF plan. Then it can improve all project construction parameters.

9. **References**

- CII (2002), "Prefabrication, Preassembly, Modularization, and Offsite Fabrication in Industrial Construction: A Framework for Decision-Making", *RS 171-1*, Construction Industry Institute, Austin, TX
- Haas, C. and Fagerlund, W. (2002), "Preliminary Research on Prefabrication, Pre-assembly, Modularization, and Off-site Fabrication in Construction", *RR 171-11,* Construction Industry Institute, Austin, TX
- Haas, C. and Song, J. (2002), "Development of a Decision-Support Tool for Prefabrication, Pre-assembly, Modularization, and Off-site Fabrication", *RR 171-12,* Construction Industry Institute, Austin, TX

22. Design for Reliability

1. **Practice Objectives**
   To provide a component or system that consistently functions over time and that meets or exceeds the owner's target level of acceptable failures.

2. **Key Benefits**
   Optimize reliability - reduced down time for repair and replacement and lower associated costs balanced against the capital cost required for a given level of expected reliability.

3. **Influence on Project Value Objectives**
   - O&M Safety .... +
   - Capital Cost Reduction .... –
   - O&M Efficiency .... + +
   - Product/Plant/Service Quality .... + +
   - Environmental Stewardship .... +

4. **Practice History/ Maturity**
   Practice is very mature. Reliability evaluation is a critical aspect of any process facility.

5. **How Common**
   Reliability is a basic quality issue. It is informally universal, though not always deliberate. Practice is often mandated by regulations and codes.

6. **Best Circumstances for Application**
   Benefits from this practice are leveraged when one or more of the following circumstances exist:

- Projects with a high cost or high consequences of downtime (i.e. life safety, revenue, system service, etc.).
- Remote site location or limited transportation access that complicates repair and replacement efforts.
- Equipment-intensive projects.

7. Limitations and Pre-Requisites
The design must meet or exceed all applicable government, regulatory agency and industry regulations, codes and standards for reliability.

8. Linkage with DE
Related to mechanical reliability modeling, this practices supports design effectiveness particularly for owner goals of O&M efficiency and product/plant quality.

9. **References**

- Crowe, D. and Feinberg, A. (2001), *Design for Reliability*, CRC, Boca Raton, FL.
- Oh, H. and Kuo, W. (1995), *Design for Reliability*, IEEE, New York, NY.
- PIP (1998), "Benchmarking of Reliability Indicators for Rotating Machinery" *REEE002,* PIP Pub, Austin, TX

23. Design for Schedule Performance

1. Practice Objectives
Reduce the time between project authorization and project in use. Design phase strategies and tactics include:

- Selection of equipment, materials and systems having short lead times, quick and efficient field installation (i.e. PPMOF, constructability analyses).
- Sequenced release of design packages in accordance with construction sequence (fast-tracking).
- Early design for pre-purchase of long lead items.
- Designing so that multiple adjacent commodities, services or areas can be worked in parallel.

2. Key Benefits
It allows management to delay, to the last possible moment, the decision to build, while bringing the facility on-line at the earliest possible time thereafter. It also reduces construction-financing costs by shortening the construction duration.

3. **Influence on Project Value Objectives**
   - Capital Cost Reduction .... –
   - Schedule Reduction .... + +

4. **Practice History/ Maturity**
   Practice is very well established. The approach increased in levels of formality in the 1980s.

5. **How Common**
   It is almost a standard procedure in the bio-pharma industry, power business, mining and metals business, petroleum industry and chemical industry and related time-to-market critical process industries.

6. **Best Circumstances for Application**
   Benefits from this practice can be achieved when one or more of the following circumstances exist:
   - Harsh site climate or seasonal effects on construction or inhospitable working environment.
   - Project is extremely schedule-driven.
   - Project is driven by regulatory milestones.
   - Some major equipment or systems are long-lead procurement/

7. **Limitations and Pre-Requisites**
   This practice requires that:
   - A firm project scope, design criteria and conceptual design can be established early in the design phase.
   - The design team and construction manager have adequate previous experience with the project type to:
     - Establish an effective project plan prior to or at the start of the design phase.
     - Anticipate what provisions must be made in early design packages and pre-purchases to accommodate the work in later packages.
     - Manage the budget contingency to deal with changes due to starting construction prior to completion of the design.
     - An effective communication and decision procedure among the owner-designer.

   Prerequisites include a driver for early project completion, resources available to implement the measures recommended by a project acceleration plan and a solid understanding of the project schedule. Risks include heavy redesign, procurement, and reconstruction costs, and delays due to long lead items that are not ordered.

8. **Linkage with DE**
Practice allows management to delay, to the last possible moment, the decision to build, while bringing the facility on-line at the earliest possible time thereafter. It forces the owner-designer-construction team to communicate early in the project and agree to parameters and assumptions regarding the final design. This communication process supports a range of design effectiveness practices.

9. **References**

- CII (1988) "Concepts and Methods of Schedule Compression", *RS 6-7*, Construction Industry Institute, Austin, TX
- CII (2007) "Trade-Off Between Cost and Schedule", *RS 214-1*, Construction Industry Institute, Austin, TX
- CII (1995) "Schedule Reduction", *RS 41-1*, Construction Industry Institute, Austin, TX
- Riggs, L. (1986), "Cost and Schedule Control in Industrial Construction" *SD-24,* Construction Industry Institute, Austin, TX

24. Design for Security

1. **Practice Objectives**
Design for the protection of buildings, occupants, and assets within them from threats, including: Unauthorized entry, insider threats, explosive threats, ballistic threats, biological or chemical threats and cyber- and information-security threats

2. **Key Benefits**
Advantages include the elimination or reduction of damage or loss of facilities, personnel, and other assets.

3. **Influence on Project Value Objectives**
- Security .... + +
- Regulatory & Standards Compliance ...... +
- Capital Cost Reduction .... –
- O&M Efficiency .... –
- Schedule Reduction .... –

4. **Practice History/ Maturity**
Security considerations have been applied to the design and construction of military facilities for decades. However, facility security in the private sector was largely focused upon the protection of assets from theft or industrial espionage

and protection of the workforce from physical harm by other individuals. An increased awareness of the need for security design and the necessity to address a broader array of threats resulted from the 9/11/2001 terrorist attacks at the WTC in NYC, and other recent (last 10-15 years) domestic bombings, including Oklahoma City's Alfred P. Murrah Federal Office Building, Atlanta's Centennial Park, and other domestic (USA) and international attacks. These events have led to a proliferation of security design considerations and criteria.

5. How Common

Practice is very common. Practice has become an increasingly critical consideration and component of all major public or private sector building development. Specialists in security design are commonly used to satisfy the new requirements created as a result of recent terrorist activity.

6. Best Circumstances for Application

Benefits from this practice are leveraged when one or more of the following circumstances exist:

- Political instability.
- Information or technology theft is likely to have significant financial impact upon the owner.
- Owner/client can be a target of violent subversive groups.
- Damage to or loss of access to facility represents a significant human, economic, or nationally strategic impact.

7. Limitations and Pre-Requisites

Incorporating security considerations comes at a price. Retrofitting all existing facilities to comply with current security and protection criteria may be cost prohibitive. Security-related decisions must consider a broad range of often conflicting factors. Ultimately, security provisions can not completely eliminate all possible threats. Prerequisites include a standard or guideline for implementing security measures on a given project as well as a source of security design and construction expertise to build the security features.

8. Linkage with DE

Security issues should be addressed in coordination with other design objectives and integrated into the overall building design throughout the process to ensure a quality building with effective security.

9. References

- Betts, C. (2005) "U.S. Department of Defense Guidance for Security Engineering" *Structures 2005*, Metropolis & Beyond, New York, NY

- CII (2005) “Implementing Project Security Practices”, *IR BMM-3,* Construction Industry Institute, Austin, TX
- CII (2004), “Best Practices for Project Security”, *BMM2004-10*, Construction Industry Institute, Austin, TX
- Duwadi, S.; Kohli, V.; and Eden, J. (2006), “Surveillance and Security Technologies for Bridges and Tunnels”, *Structures Congress 2006*, Structural Engineering and Public Safety, St. Louis, MO.
- Hunter, M.; Chernikoff, R.; Wood, T.; and Malvey, M. (2003) “Lessons Learned from Utility and Infrastructure Vulnerability Assessments”, *Pipelines 2003*, New Pipeline Technologies, Security, and Safety, Baltimore, MD.
- Matthews, B.; Sylvie, J.; Lee, S.; Thomas, S.; Chapman, R.; and Gibson, E. (2006) “Addressing Security in Early Stages of Project Life Cycle” Journal of Management in Engineering, 22(4), 196-202
- Whole Building Design Guide (WBDG) Site www.wbdg.org [accessed 07/02/2007]
- Chen, Y. (2004) “Effects of Security Measures: Deterrent versus Diversion” *Journal of Aerospace Engineering*, 17(3), 113-122

25. Design for Startup

1. Practice Objectives

Understand the relationship between planning for startup, startup success and overall project success. Increase the awareness of the importance of timely and thorough planning for startup.

2. Key Benefits

Key benefits include rapid completion of startup with fewer risks of problems or re-work caused by design errors.

3. Influence on Project Value Objectives

- O&M Safety .... +
- Construction Safety .... +
- Capital Cost Reduction .... –
- Product/Plant/Service Quality .... +
- Schedule Reduction .... + +

4. Practice History/ Maturity

“Planning for Startup” was issued by CII as a report in 1998. Practiced among only the most technically advanced; CII pub. 183-1 argues for widespread deployment of this practice.

5. **How Common**
At a basic level, this practice is very common. In the heavy industrial sector planning for startup should be incorporated into every project.

6. **Best Circumstances for Application**
Benefits from this practice are leveraged when one or more of the following circumstances exist:
    - Project is extremely schedule-driven.
    - Project involves a new manufacturing process/technology.
    - Pre-shipment systems integration and testing can be very beneficial.
    - Start-up is staged, involves shutdowns, etc.

7. **Limitations and Pre-Requisites**
Practice requires detailed knowledge of startup needs in the design stage. Availability of this information may differ across industries and across owner organizations. Practice can require specialized knowledge and extensive input from owner facilities and maintenance personnel.

8. **Linkage with DE**
Planning for startup runs throughout the project and has impact on all phases of the project. Plant start-up was identified as one of the seven most significant outputs of design effectiveness.

9. **References**

    - CII (1987), "Input Variables Impacting Design Effectiveness", *RS 8-2*, Construction Industry Institute, Austin, TX
    - CII (1998), "Planning for Startup: Overview of Research", *RS 121-1*, Construction Industry Institute, Austin, TX
    - O'Connor, J.; McLeod, J.; and Graebe, G. (1999), "Planning for Startup: Analysis of the Planning Model and Other Success Drivers", *RR 121-11*, Construction Industry Institute, Austin, TX

26. Design for Sustainability

1. **Practice Objectives**
Objectives are the reduction of the negative environmental effects of construction, including preservation of health and comfort of building occupants, and improvement of building performance. Sustainability integrates goals or objectives of the owner, including operational cost savings, environmental protection and social responsibility.

2. **Key Benefits**
   Goals also include increased yields, less energy usage, and increased operating profit, and diminished waste streams. Benefits are achieved by design to provide sustainable site development, water savings, energy efficiency, environmentally appropriate materials selection and indoor environmental quality.

3. **Influence on Project Value Objectives**
   - O&M Safety .... +
   - Regulatory & Standards Compliance .... +
   - Capital Cost Reduction .... –
   - O&M Efficiency .... +
   - Product/Plant/Service Quality .... +
   - Environmental Stewardship .... + +
   - Flexibility for Future Use .... +

4. **Practice History/ Maturity**
   Setting project goals for waste generation, energy consumption/efficiency and risk minimization is a mature practice. Other aspects of sustainable design are rapidly developing.

5. **How Common**
   Setting project goals for waste generation, energy consumption/efficiency and risk minimization are common. Setting goals for ease of recycle and future dismantlement are newer and less common. Applicability during the construction phase of projects is also rather new, except for perhaps the idea of recycling of waste materials. This has a long history, but in the past, was primarily for economic reasons (to partially recoup material costs).

6. **Best Circumstances for Application**
   Benefits from this practice are leveraged when one or more of the following circumstances exist:
   - Energy supply (or availability) is limited.
   - Owner requirement for sustainability or operational energy savings.
   - Project is a federal facility or located in states that have mandated LCC analysis.
   - A reputation for sustainability can enhance market share.
   - Facility undergoes frequent reconfiguration.
   - Facility is located in an environmentally-sensitive area.
   - Quality of indoor environment is a high priority.

7. **Limitations and Pre-Requisites**
   This practice requires that the design team has access to a sustainability guide or rating system, such as the LEED/Green Building Rating System, and has

undergone training in the application of the system. Related practices such as life cycle costing require specialized techniques and detailed investigation of the costs and benefits of alternatives.

8. **Linkage with DE**
Very important to DE, project goals and standards are best influenced by sustainability objectives early in the design process.

9. **References**

- Birkeland, J. (2002) *Design for Sustainability*, Earthscan, Sterling, VA
- Gissen, D. (2003) *Big and Green: Toward Sustainable Architecture in the 21st Century*, Princeton Architectural Press, New York, NY.
- Public Technology et. al (1996) *Sustainable Building Technical Manual : Green Building Design, Construction and Operations*, Public Technology Inc., Washington D.C.
- US Green Building Council http://www.usgbc.org [last accessed 07/02/2007]
- U.S. Green Building Council. (2002) *Green building rating system ,* U.S. Green Building Council, Bethesda, MD
- U.S. Green Building Council. (2003) *Green building rating system for new construction & major renovations (LEED-NC)*, U.S. Green Building Council, Bethesda, MD

27. Design to Capacity

1. **Practice Objectives**
Limit the amount of system over-sizing and over-design to only that needed or intended. Establish and communicate system over-sizing factors in a manner that will result in a rational, economic design solution.

2. **Key Benefits**
Advantages include the reduction in facility capital cost, Total Cost of Ownership (TCO) and an increase in economic return on assets.

3. **Influence on Project Value Objectives**
- Capital Cost Reduction .... + +
- O&M Efficiency .... + +
- Schedule Reduction .... +
- Flexibility for Future Use .... +

4. **Practice History/ Maturity**
This practice is a relatively recent development. This is a Value Improvement Practice (VIP) endorsed by Independent Project Analysis' (IPA), Industry Benchmarking Conference (IBC) and many other independent consultants.

5. **How Common**
   This practice is frequently applied among the larger, more sophisticated industrial owners and EPC contractors.

6. **Best Circumstances for Application**
   Benefits from this practice are leveraged when one or more of the following circumstances exist:
   - Plant capacity and system capacity objectives are not well understood or agreed upon.
   - Existing plant may contain "hidden" capacity.
   - Understanding of Peak versus Average capacity needs and required redundancy.
   - Conservative, over-design is likely and will be costly.
   - Equipment sizing parameters are somewhat uncertain.
   - The relationships between equipment cost and capacity or size are not well understood.
   - Marginal cost of added capacity is high.
   - Owner is committed to life-cycle cost reduction analysis.

7. **Limitations and Pre-Requisites**
   Most commonly applied on design of mechanical, electrical and specialty systems for industrial facilities. Best used when system peak and Average demands are known or understood. Can also be used for structural design, where the capacity of the soils and structural loads impact the intended capacity requirements. Implementation requires special expertise.

8. **Linkage with DE**
   The practice can certainly impact the design effectiveness by achieving a more cost-effective capital project with improved life cycle costs. Design to capacity is often referenced as a subtopic of Value Engineering (VE).

9. **References**

   - Electrical Systems - IEEE - Red Book - IEEE standard 141 www.ieee.org [accessed 07/02/2007]
   - IPA homepage: www.ipaglobal.com [accessed 07/02/2007]
   - Kumar, S. and Nottestad, D. (2006), "Capacity design: an application using discrete-event simulation and designed experiments", *IIE Transactions*, 38, pp. 729-736;
   - Mechanical Systems - ASHRAE – Standard 90.2 (2004) http://www.ashrae.org [accessed 07/02/2007]

▪ Pinho, J. (2000) "A Fab is Not Built by Layout Alone: The Case for a Concurrent Utility Matix", *Semiconductor International*, http://www.semiconductor.net [accessed 07/02/2007]
▪ Structural Systems - IBC – International Building Code – Part of International Codes Committee - www.iccsafe.org [accessed 07/02/2007]

28. Risk-Based Design

1. **Practice Objectives**
Goals include conveying realistic project expectations, control budget, improve project quality for all stakeholders. May also be tied to security related risk based design (see security topic).

2. **Key Benefits**

3. **Influence on Project Value Objectives**
   - Security .... + +
   - O&M Safety .... + +
   - Construction Safety .... +
   - Regulatory & Standards Compliance ...... +
   - Product/Plant/Service Quality .... +
   - Environmental Stewardship .... +
   - Flexibility for Future Use .... +

4. **Practice History/ Maturity**
Broadly, risk based design concepts have been used for a long time. Practice is related to or can be seen as performance based design. Its use in lieu of conventional means for designing commercial buildings/structures is a fairly new concept in the US (approx 10 years).

5. **How Common**
Risk based design is commonly practiced by industrial, military, and energy companies. Practice is applied to unique commercial construction circumstances. The practice of performance based risk based design is more commonly practiced in overseas construction (New Zealand, UK, developing Asian nations, etc.)

6. **Best Circumstances for Application**
Benefits from this practice are leveraged when one or more of the following circumstances exist:
   - Damage to or loss of access to facility represents a significant human, economic, or nationally strategic impact.

- Uncertain, high-impact design drivers exist, such as market conditions, feedstock properties, severe force-majeur events, soil/geology properties, etc.
- Statistical models exist pertaining to user needs, component properties, operating conditions, failure causes, system interaction.

7. **Limitations and Pre-Requisites**
   Risk management can be undertaken by different organizations at different stages of the project design, as well as during construction, maintenance and demolition. Implementation requires special expertise

8. **Linkage with DE**
   Risk based design practice may significantly affect the final deliverable product. With performance based projects, stakeholders may employ some form of risk based design that may impact budget, constructability, and longevity. Risk Priority Numbers (RPNs), which prioritize design concerns, are used by Failure Mode and Effects Analysis (FMEA) to evaluate design.

9. **References**

- Calafiore, G. and Dabbene, F. (ed.) (2006). *Probabilistic and Randomized Methods for Design under Uncertainty*, Springer, London, UK;
- Descheneaux, R. and Stone, H. (2006) "Risk Based Design", *The Military Engineer*, 98(641), p. 65-66
- Gelder, P. and Roos, A. (2001) *Risk Based Design of Civil Structures*, Delft University of Technology, Delft, Netherlands.
- Simm, J. D., Heald, G., Cruickshank, I. C. and Read, S. J. (1998). "Risk assessment and new risk management protocol for use in construction of coastal engineering works" *Coastline, Structures and Breakwaters*, Thomas Telford Ltd., London, pp. 148-160;
- Thunnissen, D. (2006). *Propagating and mitigating uncertainty in the design of complex multidisciplinary systems*, ProQuest/UMI.

29. Value Engineering in Design

1. **Practice Objectives**
   Promote economy of design by optimizing design solutions on a functional basis.

2. **Key Benefits**
   Reduction in facility capital costs and/or facility operating costs (life-cycle costs).

3. **Influence on Project Value Objectives**
   - Capital Cost Reduction .... + +
   - O&M Efficiency .... +
   - Schedule Reduction .... +

4. **Practice History/ Maturity**
   VE was initiated by General Electric in the 1950s, endorsed by many government agencies in the 1970s, and is now thoroughly supported by SAVE International (an organization dedicated to supporting and enhancing the value methodology). *Process Simplification* (PS) is a VE spin-off design practice suited for the process-oriented industrial sector.

5. **How Common**
   The practice is very commonly applied on medium- to large-sized government projects, including large transportation and transit projects. Many significant large private project owners (such as General Motors and Pratt & Whitney) also apply this practice frequently. Process Simplification is practiced by many large industrial owners and engineering contractors.

6. **Best Circumstances for Application**
   Benefits from this practice are leveraged when one or more of the following circumstances exist:
   - Previous similar projects have suffered from substantial scope creep.
   - The project budget is very tight or the current cost forecast is significantly over budget.
   - Owner is committed to life-cycle cost reduction analysis.
   - Related market cost pressures are ever increasing.
   - Project is a federal facility or located in states that have mandated LCC analysis.
   - Conservative, over-design is likely and will be costly.
   - The project has some unique challenges that will require unique solutions.

7. **Limitations and Pre-Requisites**
   The practice focuses on cost, rather than other project value objectives (such as project schedule, safety, or quality performance). Yet the process, if expertly customized, is flexible enough to accommodate a variety of value objectives. A trained VE facilitator or consultant is generally needed to plan and successfully execute a VE workshop. VE workshops that are conducted too late can result in schedule delays.

8. **Linkage with DE**
   VE and PS can definitely enhance overall design effectiveness.

9. **References**
   See www.value-eng.org for a near complete listing of related references and resources.

30. Vendor Integration & Design for Supply Chain

1. **Practice Objectives**
   Account for supply chain capabilities during design to smooth flow of materials to site, including engineered-to-order equipment and logistics. Set up organization to select the right component, select the right suppliers, and package design information consistent with supply chain integration plan.

2. **Key Benefits**
   Vendor integration and supply chain management can support a range of benefits, including faster construction times, improved facility efficiency through improved equipment selection, as well as decreased risk of delivery delays and costly construction re-work through faulty design coordination with engineered equipment.

3. **Influence on Project Value Objectives**
   - Security .... +
   - Capital Cost Reduction .... +
   - O&M Efficiency .... +
   - Design & Construction Quality .... +
   - Schedule Reduction .... +

4. **Practice History/ Maturity**
   Informally, vendor integration and supply chain management is widely practiced on projects through planning for long-lead time items, etc. Supply chain management and vendor integration is an increasingly mature practice in the manufacturing industry, and is an increasing area of interest in the construction industry (particularly in the industrial sector).

5. **How Common**

Basic aspects of the practice are very common, including involving key suppliers in design review, and reviewing current market lead-time conditions. More advanced coordination is becoming more common.

6. Best Circumstances for Application

Benefits from this practice are leveraged when one or more of the following circumstances exist:

- Project has highly complex design geometry.
- Project involves repetitive shop work tasks.
- Critical, major materials are in short supply and/or are difficult to transport.
- Pre-shipment systems integration and testing can be very beneficial.
- Some major equipment or systems are long-lead procurement.
- Supplier alliances or long-standing relationships exist.
- Purchased components are engineered-to-order or often customized.
- Owner and/or contractor have purchasing leverage (i.e. high-volume).

7. Limitations and Pre-Requisites

Practice requires a design team that is open in supplier involvement, which may increase first costs in coordination and design staffing. Specialized procedures and contracts may need to be in place to support the practice.

8. Linkage with DE

Vendor integration and design for supply chain is an increasingly important aspect of design effectiveness given the increasing value-added activities that occur off-site.

9. References

- Tommelein, I.; Walsh, K.; and Hershauer, J. (2003), "Improving Capital Projects Supply Chain Performance", *RR 172-11,* Construction Industry Institute, Austin, TX.

Appendix D: Best Circumstances for DEP Application

A. Owner/Project Team Characteristics

1. New contract/delivery process or new technology, or recent major industry event prompts the need for a new or modified design process (1)
2. Design team has limited experience with related technologies (2)(11)
3. The project is for a large organization with multiple similar facilities, or is a common project type within an industry sector (3)
4. Large organization with broad EPC or turn-key like breadth of scope (4)
5. Company culture is receptive to experience sharing (4)
6. Project involves many first-time participants (4)
7. Project team is large and complex (5)(8)
8. Best or most economical technical resources (i.e. specialists) are geographically separated (9)
9. Owner/client can be a target of violent subversive groups (24)
10. Owner and/or contractor have purchasing leverage (i.e. high-volume) (30)

B. Project Objectives/Project Performance

11. Projects with a high cost or high consequences of downtime (i.e. life safety, revenue, system service, etc.) (3)(16)(17)(19)(22)
12. Project definition is ineffectively established or likely to change (5)
13. Previous similar projects have suffered from substantial scope creep (5)(29)
14. The team is trying to beat a historical design performance benchmark (6)
15. Owner desires assurance of design progress (6)
16. Owner is committed to life-cycle cost reduction analysis (7)(10)(15)(16)(27)(29)
17. Project is extremely schedule-driven (11)(21)(23)(25)
18. Requirement for consistent quality, e.g. Nuclear steam pipe welding (12)(13)(19)
19. Owner requirement for sustainability or operational energy savings (15)(26)
20. Project is driven by regulatory milestones (23)
21. The project has some unique challenges that will require unique solutions (29)

C. Budget/Cost/Economics

22. Insurance savings may result or liability risks can be mitigated (2)
23. The team is trying to beat a historical project cost benchmark or is market-price-driven (5)(14)
24. The project budget is very tight or the current cost forecast is significantly over budget (5)(29)
25. An incentive or compensation is based on design productivity (6)

26. Non-virtual team collaboration costs are too high (9)
27. Related market cost pressures are ever increasing (14)(29)
28. Information or technology theft is likely to have significant financial impact upon the owner (24)
29. A reputation for sustainability can enhance market share (26)
30. Marginal cost of added capacity is high (16)(27)

D. Site Conditions/Existing Facility

31. Accessibility-related challenges within site (11)(16)
32. Shortage of skilled labor (11)(12)(13)(21)
33. Harsh site climate or seasonal effects on construction or inhospitable working environment (11)(13)(18)(19)(21)(23)
34. Projects which have life-critical construction safety exposures that designers can address (i.e. elevated work, confined spaces, combustible/explosive materials, heavy lifting, deep excavations and excavations around existing utilities, sources of high-energy, etc.) (12)(13)(21)
35. High local wage rates at project site (21)
36. Limited lay-down or pre-fab space at site or excessive work density (21)
37. Remote site location or limited transportation access (21)(22)
38. Political instability (21)(24)
39. Facility is located in an environmentally-sensitive area (16)(26)
40. Existing plant may contain "hidden" capacity (27)

E. Facility Scope & Characteristics

41. No standard design work process exists for an emerging project type, or an existing process needs updating (1)
42. The project has repetitive complex components (3)
43. Use of repetitive or high volume elements or components (4)(12)
44. Project size/effort is large (6)
45. Flexibility in facility siting, orientation, and envelope (15)
46. Energy supply (or availability) is limited (15)(26)
47. Project is a federal facility or located in states that have mandated LCC analysis (15)(26)(29)
48. Facility has high occupancies (20)
49. Facility in which aesthetics is important to public perception, sales, or rental potential (20)
50. Facilities that benefit from orientation and way-finding schemes (20)
51. Damage to or loss of access to facility represents a significant human, economic, or nationally strategic impact (24)(28)
52. Facility undergoes frequent reconfiguration (16)(26)

53. Quality of indoor environment is a high priority (26)
54. Plant capacity and system capacity objectives are not well understood or agreed upon (27)
55. Uncertain, high-impact design drivers exist, such as market conditions, feedstock properties, severe force-majeur events, soil/geology properties, etc. (28)

F. Technologies/Manufacturing Process

56. Visual simulation can significantly enhance or optimize accessibility, sequencing, layout/configuration, or user preferences; or physical interference detection will be very beneficial; or automated material take-offs are desirable (7)
57. New related technologies are emerging; best available technology may have changed (10)(11)
58. Technology selection circumstances have changed (i.e. market, prices, regulations, etc.) (10)(11)
59. Project involves repetitive shop work tasks (11)(12)(30)
60. Project involves a new manufacturing process/technology (18)(25)
61. Statistical models exist pertaining to user needs, component properties, operating conditions, failure causes, system interaction (28)

G. Project Design

62. Owner requests a design process model (1)
63. Formal design verification is required by the owner (2)
64. Maintaining a design standard is critical or regulatory approval is constraining (5)
65. Design can benefit from a scenario simulation approach (7)(8)
66. Multi-system interoperability offers higher levels of optimization (8)
67. There is benefit from early electronic design approach, or manual design approach is time-consuming (8)
68. Design software systems offer higher levels of optimization (8)
69. Project has highly complex design geometry (8)(11)(30)
70. Automated design data can facilitate or drive automated process (12)
71. Conservative, over-design is likely and will be costly (27)(29)

H. Facility Operations/Maintenance

72. Projects that involve labor-intensive maintenance operations (17)
73. Projects with many equipment options that vary in durability and maintenance requirements (17)
74. Projects that can benefit from predictive maintenance technologies (17)

75. Projects that involve bulky, heavy, or hazardous operations and/or maintenance (17)(18)(19)
76. Facility operations require high precision in placement and handling (18)
77. Computer-based controls improve facility performance (18)
78. Real-time product process tracking is required (for high-value inventory) (18)
79. Shortage of needed operators (labor) or high cost of labor (18)
80. Start-up is staged, involves shutdowns, etc. (25)

I. Materials/Equipment/Procurement/Supply Chain

81. Integrated suppliers can benefit from exchange of digital design data (8)
82. Critical, major materials are in short supply and/or are difficult to transport (11)(30)
83. Pre-shipment systems integration and testing can be very beneficial (21)(25)(30)
84. Equipment-intensive projects (22)
85. Some major equipment or systems are long-lead procurement (23)(30)
86. Equipment sizing parameters are somewhat uncertain (27)
87. The relationships between equipment cost and capacity or size are not well understood (27)
88. Supplier alliances or long-standing relationships exist (30)
89. Purchased components are engineered-to-order or often customized (30)

J. Procedures & Communications

90. Recent related code changes have occurred (2)(5)
91. The project requires high levels of regulatory qualification and/or inspection (3)(5)
92. Lessons-learned are documented and can be shared (4)
93. Communication of design configuration with owner/user stakeholders (7)
94. Team benefits from project-centric information exchange system (9)

DEP	Number of related Characteristics
Standard Design Delivery Process	3
Design Quality Management /QA/QC	4
Design Standardization/PIP	4
Lessons-Learned System/Learning Organization Approaches	5
Change Management	8
Design Productivity Tracking	4
3D & 4D CAD	4
Design Automation & Software	7
Virtual Teams	3
Technology Tracking & Selection	3
Design for Constructability	10
Design for Construction Automation	6
Design for Construction Safety	4
Design to Cost	2
Design for Energy Efficiency	5
Design for Expandability	6
Design for Maintainability	5
Design for Operational Automation	7
Design for Operational Safety	4
Design for People	3
Design for PPMOF	9
Design for Reliability	3
Design for Schedule Performance	4
Design for Security	4
Design for Startup	4
Design for Sustainability	7
Design to Capacity	7
Risk-Based Design	3
Value Engineering in Design	7
Vendor Integration & Design for Supply Chain	8

Appendix E: DEP Selection Tool User Manual

Before Starting:

- *Place the DEPSeltoolProgram.xls and the DEPinfo.doc in the same file directory.*
- *Select "Enable Macros" when prompted at the start of the program.*

Selection Tool Introduction:

This tool is intended to facilitate the selection of CII Design Effectiveness Practices for implementation on a project. This tool takes into consideration three primary selection factors:

- Current Project Phase
- Desired Project Benefits and their relative importance
- Project Specific Characteristics

The selection tool provides guidance on which DEPs may offer the most value for your project. The results are intended to initiate a team dialog on which DEPs should be considered for implementation.

Selection Tool Page Progression:

The selection tool follows a logical progression of pages or screens for data entry. The screens are listed immediately below, and explained in the following sections of this appendix.

1. Introduction
2. Project Information
3. Introduction to Screening
    a. Desired Benefits from DEP implementation
    b. DEPs to Exclude from analysis
4. Confirmation of DEPs for consideration
5. Project Characteristics
6. DEP Recommendation Results
    a. View Project Characteristic Drivers
    b. View DEP Score Chart

Page by Page Walkthrough:

Introduction:

This page presents the selection tool's purpose and limitations. Click on the "Proceed to DEP Selection" button to proceed.

Project Information:

This page prompts the user to input basic information about the project for which the DEP selection is being implemented. None of the fields are required to proceed, but is recommended for record keeping. Click the "Start DEP Selection" button to proceed.

Introduction to Screening of DEPs:

This page asks the user to indicate the project design phase. Note that DEP implementation benefits diminish the later the project is in the design phase. This page also presents the user with the option of further screening their DEP selection by Desired Benefits and/or excluding DEPs. Click the check-boxes to select the any further screening options if desired. Click the "Continue" button to proceed.

Desired Benefits:

This optional screening process asks the user to input the desired benefits from DEP implementation. The degree of desired benefits can be assigned a Low, Medium, or High value, in addition to a Not Applicable (N/A) option. At least one desired benefit must be selected. If the user does not select the "Desired Benefits" screening option from the previous page, all desired benefits would be considered as "High" by default. Click the "Continue" button to proceed.

DEPs to Exclude:

This page lists all of the 30 DEPs and allows the user to check the DEPs to be excluded from analysis. Click the check boxes to activate or deactivate the selection. Click the "Continue" button to proceed.

Confirmation of DEPs for Consideration:

This page asks the user to confirm the set of DEPs that will be considered for analysis. The set is developed from the DEPs that suit the project Timing Phase, in addition to any limitations on desired benefits and excluded DEPs from the optional screening pages. The user can transfer DEPs from the Included to the Excluded list (and visa versa) by clicking the DEP in the list box. Click the "Update List as Modified" button to view the updated list and transfer selected DEPs from one list to the other. Clicking the “Accept & Continue” button will also update the lists, and will send you to the next step in the DEP selection process.

Project Characteristics:

The user is asked on this page to select the characteristics that best describe their project. Click the checkboxes next to each project characteristic to indicate that it matches the project. Click the “Continue” button at the end of the list to proceed to the results page.

DEP Recommendation Results:

This page presents the recommended DEPs ranked by decreasing Composite score. The DEPs can be sorted by Timing Score, Project Characteristics Score, or Desired Benefits Score by clicking on the respective buttons at the top of the table. Clicking the “Interpretation” button beneath each score will bring up a message window with further information on that Score.

At the bottom of the table are additional buttons to aid interpretation of the results. Click the “View Project Characteristics Drivers” button to view the 3 main Project Characteristics selected that influenced the DEP Characteristics Score. This page lists the top ten DEPs according to the Composite Score. Click the “View DEP Score Chart” to view the recommended DEPs and their Composite Score in chart form.

DEP Selection Tool Algorithm:

This section provides an overview of the selection algorithm to help provide insight into the selection process.

Algorithm Overview:

First, the user selects a Project Phase. Input “T”, the Timing Impact, is derived from the DEP-Timing matrix (see Table E.1) for each DEP according to the phase selected. “T” ranges from 0 to 10.

Table E.1: Abbreviated DEP-Timing Matrix

	DEP	Start of Conceptual Design	Start of Early Detailed Design	Start of Late Detailed Design
1	Standard Design Delivery Process	10	4	0
2	Design Quality Mgmt./QA/QC	10	6	2
3	Design Standardization/PIP	10	4	2
4	Lessons-Learned System/Learning Organization	10	8	6
5	Change Management	10	6	4

The user then selects the Desired Benefits from the list of Project Value Objectives (Figure E.1). A level multiplier is determined for each PVO according to the selected level, with N/A = 0, Low = 0.33, Med = 0.67, and High = 1. The level multiplier value is then normalized to the maximum level selected (i.e., selecting all PVOs as "Low" will give the same multipliers as selecting them all as "Med").

Security	(•) N/A	( ) Low	( ) Med	( ) High
O&M Safety	( ) N/A	( ) Low	(•) Med	( ) High
Construction Safety	( ) N/A	( ) Low	( ) Med	(•) High
Regulatory & Standards Complianc	( ) N/A	(•) Low	( ) Med	( ) High
Capital Cost Reduction	( ) N/A	( ) Low	( ) Med	(•) High

Figure E.1: Sample of the Desired Benefits selection options

The DEP-PVO Matrix contains a score for each DEP corresponding to a PVO. The scores indicate the influence (both positive and negative) of a DEP on a PVO. Scores can be: -0.25, 0, 0.5, 1 (Table E.2). The level multipliers for each PVO are applied to their corresponding columns, producing a modified DEP-PVO matrix. A Desired Benefits Score, "D", is calculated for each DEP from the non-zero average of the DEP-PVO values of the corresponding DEP. "D" ranges from -0.25 to 1.

Table E.2: Abbreviated DEP-PVO matrix

		Security	O&M Safety	Construction Safety	Regulatory & Standards	Capital Cost Reduction	O&M Efficiency	Product/Plant/Service	Design & Construction	Schedule Reduction	Environmental Stewardship	Flexibility for Future Use
11	Design for Constructability	0	0	**1**	**0.5**	**1**	0	**0.5**	**1**	**1**	0	0
12	Design for Constr. Automatn.	0	0	**1**	0	**0.5**	0	0	**0.5**	**0.5**	0	0
13	Design for Constr. Safety	0	**0.5**	**1**	**1**	**0.5**	0	0	**0.5**	**0.5**	0	0
14	Design to Cost	0	0	0	0	**1**	**-0.25**	0	0	**-0.25**	0	**-0.25**

- ☐ Project definition is ineffectively established or likely to change
- ☐ Previous similar projects have suffered from substantial scope creep
- ☐ The team is trying to beat a historical design performance benchmark
- ☐ Owner desires assurance of design progress
- ☐ Owner is committed to life-cycle cost reduction analysis
- ☐ Project is extremely schedule-driven

Figure E.2: Sample of Project Characteristics

Next, the user selects the appropriate project characteristics (Figure E.2) for each DEP. Each DEP has from 2 to 10 project characteristics that may be selected. Project characteristics allow fine-tuning of DEP applicability for the project in question. The Project Characteristics score, "C", increases for each DEP as more project characteristics corresponding to that DEP are selected. "C" is derived as follows:

$$C = 0.2 + 0.8\left(\frac{X}{Y}\right)^{\frac{1}{2}}$$

Where: X = Selected number of Characteristics for a given DEP
Y = Total number of Characteristics for a given DEP

The equation causes "C" to range from 0.2 to 1, starting with a steep slope at 0.3 that decreases as "C" reaches 1 (See figure E.3). The scoring of C ensures that the first few project characteristics for a given DEP have a greater weight in measuring applicability than do the last few project characteristics selected. This scoring avoids the possibility that a DEP score with just one or two selected characteristics is inadvertently excluded from analysis.

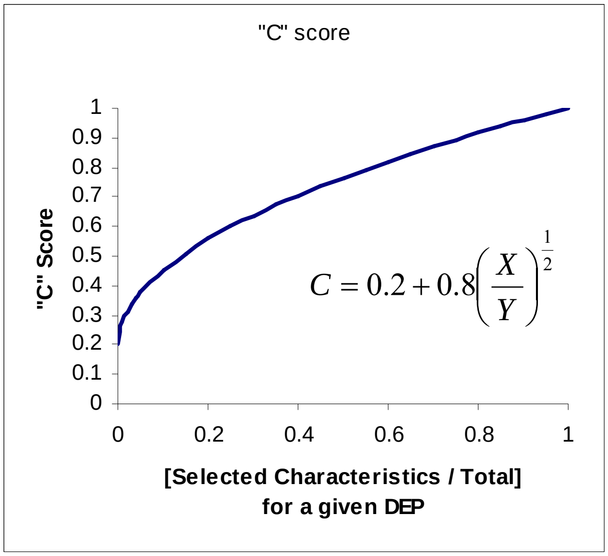

Figure E.3: Plot of the "C" Score equation

The Composite DEP Score is calculated as: DEP = T*(0.6*D + 0.4*C). The DEPs are all ranked according to their Composite score, with DEPs with a score higher than 5 being highly recommended. DEPs with a score 3 to 5 are recommended for consideration, and those below 3 are not recommended for implementation.

Troubleshooting:

Cannot Proceed Beyond Introduction Page:

Problem: Clicking the "Continue" button on the introduction page does nothing.
Solution: Make sure to "Enable Macros" when prompted at the start of the file launch. Otherwise, make sure your macro security settings are on "medium" by selecting tools → options → security (tab) → macro settings.

Disappearing or Inappropriately-Sized Buttons:

Problem: Buttons are not being displayed, or they are being displayed in an inappropriate size that is causing buttons to be displayed in an overlapping fashion.
Solution: Set your screen resolution to 1024x768. Also make sure your program window is on full-screen view. Note: Some old-model projectors are also known to have problems displaying buttons.

No "Project Characteristics" Buttons:

Problem: No buttons displayed on the "Project Characteristics" page.
Solution: Scroll to the bottom of the page using the scroll bar or the mouse wheel.

No “Recommended DEPs” and “DEP Drivers” Buttons:

Problem: No buttons displayed on the page
Solution: Scroll to the bottom of the page using the scroll bar or the mouse wheel.

DEP Characteristics Drivers Has Several “N/A” Values:

Problem: The Project Characteristic Drivers for the recommended DEPs have N/A values.
Solution: This is due to fewer than three project characteristics affecting this DEP. This is quite normal and is expected to be the case when fewer project characteristics are chosen. Results presents should be valid.

Small Text:

Problem: The text is too small to read.
Solution: Set your screen resolution to 1024x768. You can also increase the window zoom by selecting View → Zoom from your toolbar

Buttons Do Not Activate:

Problem: Clicking the button does nothing.
Solution: Click on a cell away from the buttons and try again. If that does not work, there is the rare possibility that you are in Control Toolbox Design Form. Click on View → Toolbars → Control Toolbox and toggle the Design Mode icon on and off. If buttons can be dragged and dropped, then you are in Design Mode and the buttons are not active. Once you toggle Design Mode off, turn off the Control Toolbox and proceed with the program.

Checkbox Selections Will Not Toggle:

Problem: Clicking on a selection in the “DEPs to Exclude” and “Project Characteristics” pages does not toggle the checkboxes
Solution: Click the checkbox next to the text. However, if Checkboxes are being dragged instead of activating, then see the “Buttons Do Not Activate” problem above to toggle Control Toolbox Design Mode off

“Learn More About DEPs” Button Does Nothing:

Problem: Clicking the “Learn More About DEPs” button does nothing.
Solution: Make sure the accompanying “DEPinfo.doc” file is installed in the same directory as the program’s *.xls file.

Appendix F: DEP Selection Tool Validation Survey Sample

Manual DEP Selection Process

Note: This information will be held in STRICT CONFIDENCE. No data will ever be publicly associated with any name of any company or individual.

The purpose of the survey is to establish the validity of the Design Effectiveness Practice (DEP) Selection Tool as it is currently designed and to identify any needs for improvement. This assessment should be completed in the context of a specific project (that you name below). There are three parts of the validation process in the sequence presented:

1. Complete this workbook and return to U.T. researchers
2. Apply the Excel-based DEP Selection Tool (which will be sent to you upon completion of step 1) and return the completed file to U.T. researchers
3. If asked, participate in a phone conversation with U.T. researchers to discuss any discrepancies between this manual selection process and the automated selection process.

THANK YOU VERY MUCH FOR ASSISTING US WITH THIS DEVELOPMENT!

If you have any questions about the process, please contact Ra'ed Jarrah at 214-491-0755 (cell) or 512-471-8417 (office) or email at raedjarrah@mail.utexas.edu.

I. Project and Contact Information

Project Name	
Project Location	
Project Type & Size	
Project Telephone	
Name of Survey Respondent	
Title/role relative to the named project	
Company Name	
Contact Information	(Phone) (E-mail)

II. Gut Feel Selection

A. Establish the DEP Selection Pool

For any project, which Design Effectiveness Practices (DEPs) would you normally consider for selection? Please ***circle or check the number*** associated with each DEP which you wish to consider in the selection. Exclude those DEPs that you and/or your organization are not familiar with.

#	Design Effectiveness Practice	#	Design Effectiveness Practice
1	**Standard Design Delivery Process**	16	**Design for Expandability**
2	**Design Quality Mgmt./QA/QC**	17	**Design for Maintainability**
3	**Design Standardization/ Process Industry Practices**	18	**Design for Operational Automation**
4	**Lessons-Learned System/ Learning Organization Approaches**	19	**Design for Operational Safety**
5	**Change Management**	20	**Design for People**
6	**Design Productivity Tracking**	21	**Design for Prefabrication, Preassembly, Modularization, and Offsite Fabrication (PPMOF)**
7	**3D & 4D CAD**	22	**Design for Reliability**
8	**Design Automation & Software**	23	**Design for Schedule Performance**
9	**Virtual Teams**	24	**Design for Security**
10	**Technology Tracking & Selection**	25	**Design for Startup**
11	**Design for Constructability**	26	**Design for Sustainability**
12	**Design for Construction Automation**	27	**Design to Capacity**
13	**Design for Construction Safety**	28	**Risk-Based Design**
14	**Design to Cost**	29	**Value Engineering in Design**
15	**Design for Energy Efficiency**	30	**Vendor Integration & Design for Supply Chain**

B. Unstructured Intuition DEP Assessment

Based on your overall “Gut Feel” and considering any and all factors from the list of DEPs selected above, what are “top 10” DEPs you would select for this project? Please arrange your choice in two groupings according to priority or preference. List the numbers from the selections in Part II.A (above). No further ranking is needed.

Top 10: First Tier		**Top 10: Second Tier**	
1		*6*	

2		*7*	
3		*8*	
4		*9*	
5		*10*	

III. Structured Rigorous Assessment

A. Establishment of Desired Project Value Objectives

Please **circle or check the level of significance** of each Project Value Objective for your named project.

#	Project Value Objectives	Level Desired			
1	Security	N/A	Low	Medium	High
2	O&M Safety	N/A	Low	Medium	High
3	Construction Safety	N/A	Low	Medium	High
4	Regulatory & Standards Compliance	N/A	Low	Medium	High
5	Capital Cost Reduction	N/A	Low	Medium	High
6	O&M Efficiency	N/A	Low	Medium	High
7	Product/Plant/Service Quality	N/A	Low	Medium	High
8	Design & Construction Quality	N/A	Low	Medium	High
9	Schedule Reduction	N/A	Low	Medium	High
10	Environmental Stewardship	N/A	Low	Medium	High
11	Flexibility for Future Use	N/A	Low	Medium	High

B. DEP Appropriateness for Desired Benefit(s)

Please list the DEP numbers previously selected in Part II.A (page 2) that you feel support any of the targeted Project Value Objective(s) previously selected in Part III-A (above).

C. Phase of Project When DEP Implementation Can Occur

What is the current phase of the project? Please select the letter from the following list.

ID	Project Phase
A	Approximately at Start of Conceptual Design (0% Design Complete)
B	Start of Early Detailed Design (20% Design Complete)
C	Start of Late Detailed Design (60% Design Complete)

D. DEP Appropriateness for Project Phase

Please list the DEP numbers previously selected in Part II.A (page 2) that could, in your opinion, be effectively implemented during *or after* the phase indicated above.

E. Appropriateness/Suitability to the Project

From the listing of DEPs previously selected in Part II.A (page 2), which DEPs (by number) would be *most responsive to the unique characteristics and challenges of this project*? Please try to list between 5 and 10 DEPs, and if possible, identify the project characteristics or challenges they address.

DEP #	Unique Characteristics / Challenges of Project

F. Conclusions from Structured Rigorous Assessment

Please review your responses to Section III parts B, D, and E (pages 3-4) and based on those observations indicate the numbers of the top 10 DEPs for your project. As before, please arrange this in First Tier and Second Tier groupings

Top 10: First Tier		**Top 10: Second Tier**	
1		*6*	
2		*7*	
3		*8*	
4		*9*	
5		*10*	

This completes the manual process.

The automated DEP selection tool will be sent to you soon. Thank you again for your effort in this validation process.

Please send this completed documentation to:

Raed Jarrah
Department of Civil Engineering
ECJ 5.402A
University of Texas
Austin, TX 78712

or Fax to: 512-471-3191
or Email to: raedjarrah@mail.utexas.edu

Appendix G: DEP Selection Tool Validation Phone Interview Guide Sample

Evaluation of the DEP Selection Tool – Phone Interview Guide

Participant(s) Name:

Organization:

Project Description:

Interview Date:

1. Did you find the Automated Tool helpful in selecting the DEPs?

☐ *Yes*
☐ *No* <Ask to explain in #3>

2. How confident were you in assessing the Project Characteristics?

☐ *Mostly Confident*
☐ *Somewhat Confident*
☐ *Not Very Confident*

3. Below are the DEP rankings as generated by the **DEP Selection Tool**. In comparison with the Structured Manual rankings, please indicate the appropriateness of the Selection Tool DEP ranking for your given project with:

g) The two ranks are very similar
h) This DEP was deliberately excluded from the analysis
i) I am not familiar with this DEP
j) Recommended DEP is not appropriate because…
k) Recommended DEP is appropriately ranked
l) Recommended DEP is appropriate for the project, but with a different rank

Please provide any comments that could help explain any differences.

PART 3

Tool Rank	Selection Tool Recommended DEPs	Ranking in Structured Manual	Assess Appropriateness for Project	Because…
1			☐ a) The two ranks are very similar ☐ b) This DEP was deliberately excluded from the analysis ☐ c) I am not familiar with this DEP ☐ d) Tool Recommended DEP is not appropriate because… ☐ e) Tool Recommended DEP is appropriately ranked ☐ f) Tool Recommended DEP is appropriate for the project, but with a different rank	
2			☐ a) The two ranks are very similar ☐ b) This DEP was deliberately excluded from the analysis ☐ c) I am not familiar with this DEP ☐ d) Tool Recommended DEP is not appropriate because… ☐ e) Tool Recommended DEP is appropriately ranked ☐ f) Tool Recommended DEP is appropriate for the project, but with a different rank	
3			☐ a) The two ranks are very similar ☐ b) This DEP was deliberately excluded from the analysis ☐ c) I am not familiar with this DEP ☐ d) Tool Recommended DEP is not appropriate because… ☐ e) Tool Recommended DEP is appropriately ranked ☐ f) Tool Recommended DEP is appropriate for the project, but with a different rank	
4			☐ a) The two ranks are very similar ☐ b) This DEP was deliberately excluded from the analysis ☐ c) I am not familiar with this DEP ☐ d) Tool Recommended DEP is not appropriate because… ☐ e) Tool Recommended DEP is appropriately ranked ☐ f) Tool Recommended DEP is appropriate for the project, but with a different rank	
5			☐ a) The two ranks are very similar ☐ b) This DEP was deliberately excluded from the analysis ☐ c) I am not familiar with this DEP ☐ d) Tool Recommended DEP is not appropriate because… ☐ e) Tool Recommended DEP is appropriately ranked ☐ f) Tool Recommended DEP is appropriate for the project, but with a different rank	

6			☐ a) The two ranks are very similar ☐ b) This DEP was deliberately excluded from the analysis ☐ c) I am not familiar with this DEP ☐ d) Tool Recommended DEP is not appropriate because… ☐ e) Tool Recommended DEP is appropriately ranked ☐ f) Tool Recommended DEP is appropriate for the project, but with a different rank	
7			☐ a) The two ranks are very similar ☐ b) This DEP was deliberately excluded from the analysis ☐ c) I am not familiar with this DEP ☐ d) Tool Recommended DEP is not appropriate because… ☐ e) Tool Recommended DEP is appropriately ranked ☐ f) Tool Recommended DEP is appropriate for the project, but with a different rank	
8			☐ a) The two ranks are very similar ☐ b) This DEP was deliberately excluded from the analysis ☐ c) I am not familiar with this DEP ☐ d) Tool Recommended DEP is not appropriate because… ☐ e) Tool Recommended DEP is appropriately ranked ☐ f) Tool Recommended DEP is appropriate for the project, but with a different rank	
9			☐ a) The two ranks are very similar ☐ b) This DEP was deliberately excluded from the analysis ☐ c) I am not familiar with this DEP ☐ d) Tool Recommended DEP is not appropriate because… ☐ e) Tool Recommended DEP is appropriately ranked ☐ f) Tool Recommended DEP is appropriate for the project, but with a different rank	
10			☐ a) The two ranks are very similar ☐ b) This DEP was deliberately excluded from the analysis ☐ c) I am not familiar with this DEP ☐ d) Tool Recommended DEP is not appropriate because… ☐ e) Tool Recommended DEP is appropriately ranked ☐ f) Tool Recommended DEP is appropriate for the project, but with a different rank	

4. Beyond those DEPs analyzed in Section 3 above, below are additional DEPs and rankings from your **Structured Manual Process**. Please indicate the appropriateness of the Structured Manual DEP ranking for your given project with:

e) DEP already addressed in Part 3
f) DEP should remain a high priority because…
g) DEP is appropriate for project, but should not be in the top 10
h) DEP should not have been selected for this project.

Please provide any comments that could help explain any differences.

PART 4

Rank	Selected DEP in Structured Manual Process	Assess Appropriateness for Project	Because…
1		☐ a) DEP already addressed in Part 3 ☐ b) DEP should remain a high priority because… ☐ c) DEP is appropriate for project, but should not be in the top 10 ☐ d) DEP should not have been selected for this project.	
2		☐ a) DEP already addressed in Part 3 ☐ b) DEP should remain a high priority because… ☐ c) DEP is appropriate for project, but should not be in the top 10 ☐ d) DEP should not have been selected for this project.	
3		☐ a) DEP already addressed in Part 3 ☐ b) DEP should remain a high priority because… ☐ c) DEP is appropriate for project, but should not be in the top 10 ☐ d) DEP should not have been selected for this project.	
4		☐ a) DEP already addressed in Part 3 ☐ b) DEP should remain a high priority because… ☐ c) DEP is appropriate for project, but should not be in the top 10 ☐ d) DEP should not have been selected for this project.	
5		☐ a) DEP already addressed in Part 3 ☐ b) DEP should remain a high priority because… ☐ c) DEP is appropriate for project, but should not be in the top 10 ☐ d) DEP should not have been selected for this project.	

6		☐ a) DEP already addressed in Part 3 ☐ b) DEP should remain a high priority because… ☐ c) DEP is appropriate for project, but should not be in the top 10 ☐ d) DEP should not have been selected for this project.	
7		☐ a) DEP already addressed in Part 3 ☐ b) DEP should remain a high priority because… ☐ c) DEP is appropriate for project, but should not be in the top 10 ☐ d) DEP should not have been selected for this project.	
8		☐ a) DEP already addressed in Part 3 ☐ b) DEP should remain a high priority because… ☐ c) DEP is appropriate for project, but should not be in the top 10 ☐ d) DEP should not have been selected for this project.	
9		☐ a) DEP already addressed in Part 3 ☐ b) DEP should remain a high priority because… ☐ c) DEP is appropriate for project, but should not be in the top 10 ☐ d) DEP should not have been selected for this project.	
10		☐ a) DEP already addressed in Part 3 ☐ b) DEP should remain a high priority because… ☐ c) DEP is appropriate for project, but should not be in the top 10 ☐ d) DEP should not have been selected for this project.	

5. Do you have any additional comments on the DEP Selection Tool?

Advantages:

- .
- .
- .
- .

Disadvantages:

- .
- .
- .
- .

Suggestions:

- .
- .
- .
- .

6. Which of the approaches do you now prefer: the Intuition-based, the Structured-Manual or the Automated Tool?

☐ *Intuition-based*
☐ *Structured-Manual*
☐ *Automated Tool*

Thank you for your time and cooperation

Appendix H: Design Effectiveness Evaluation Criteria and Sub-Criteria

This appendix describes the Project Value Objectives sub-criteria that are used in the Design Effectiveness Evaluation Tool. Each of the 11 PVOs is associated with a number of sub-criteria that are recommended measures of design effectiveness. Sub-criteria are applicable at different phases of the project. The tables below list each sub-criterion, scale, and applicability in each of the project phases. Project phases are defined as follows:

1. Conceptual Design: 20 percent design complete
2. Detailed Design: 60 percent design complete
3. Design 100 percent complete
4. Construction complete
5. Post Occupancy Evaluation

Table H.1: Security PVO Sub-Criteria

1	Security					Timing				
1.1	Facility detects and responds to physical breaches as required					1	2	3	4	5
		NEVER	OCCASIONALLY	USUALLY	ALWAYS				x	x
1.2	Facility information systems withstand security breach tests					1	2	3	4	5
		DO NOT	OCCASIONALLY	USUALLY	TRUE				x	x
1.3	Design Plans & Specifications appropriately address construction security requirements					1	2	3	4	5
		DO NOT	OCCASIONALLY	USUALLY	DO		x	x		
1.4	Design Plans & Specifications appropriately address access to hazardous/controlled substances during construction and start-up, as required					1	2	3	4	5
		DO NOT	OCCASIONALLY	USUALLY	DO		x	x		
1.5	IP and design information are handled in a manner consistent with security requirements					1	2	3	4	5
		DO NOT	OCCASIONALLY	USUALLY	DO	x	x	x		

Table H.2: Operations and Maintenance Safety PVO Sub-Criteria

2	O&M Safety					Timing				
2.1	Design is compliant with O/M safety regulations and codes, as required					1	2	3	4	5
		IS NOT	OCCASIONALLY	USUALLY	IS			x	x	x
2.2	Design incorporates industry/corporation safety standards, best practices, and lessons-learned					1	2	3	4	5
		DOES NOT	OCCASIONALLY	USUALLY	DOES		x	x	x	
2.3	Design incorporates HAZOP, PHA, and PSM input					1	2	3	4	5
		DOES NOT	OCCASIONALLY	USUALLY	DOES		x	x	x	x
2.4	Design Incorporates O/M accessibility and ergonomics					1	2	3	4	5
		DOES NOT	OCCASIONALLY	USUALLY	DOES		x	x	x	x
2.5	Design supports safe startup/operations/shut-down/decommissioning at all levels (i.e., plant, systems, etc.)					1	2	3	4	5
		DOES NOT	OCCASIONALLY	USUALLY	DOES				x	x

Table H.3: Construction Safety PVO Sub-Criteria

				Timing				
3	**Construction Safety**							
	3.1		**Design facilitates safe construction by incorporating preventive practices derived from analysis of root cause**					
	3.1.1	**3.1.1**	**Fall protection**	1	2	3	4	5
			DOES NOT — IN SOME CASES — IN MOST CASES — DOES		x	x	x	
	3.1.2	**3.1.2**	**Electrocution**	1	2	3	4	5
			DOES NOT — IN SOME CASES — IN MOST CASES — DOES		x	x	x	
	3.1.3	**3.1.3**	**Confined spaces, including caught-between, respiratory threats, emergency egress, ...**	1	2	3	4	5
			DOES NOT — IN SOME CASES — IN MOST CASES — DOES		x	x	x	
	3.1.4	**3.1.4**	**Excavation and trench failure**	1	2	3	4	5
			DOES NOT — IN SOME CASES — IN MOST CASES — DOES		x	x	x	
	3.1.5	**3.1.5**	**Heavy lifts**	1	2	3	4	5
			DOES NOT — IN SOME CASES — IN MOST CASES — DOES		x	x	x	
	3.1.6	**3.1.6**	**Construction in operating areas**	1	2	3	4	5
			DOES NOT — IN SOME CASES — IN MOST CASES — DOES		x	x	x	
	3.1.7	**3.1.7**	**Safe access**	1	2	3	4	5
			DOES NOT — IN SOME CASES — IN MOST CASES — DOES			x	x	
	3.2		**Design is compliant with applicable construction safety codes and regulations**	1	2	3	4	5
			DOES NOT — IN SOME CASES — IN MOST CASES — DOES			x	x	

Table H.4: Regulatory and Standards Compliance PVO Sub-Criteria

			Timing				
4	**Regulatory & Standards Compliance**						
	4.1	**Design documentation facilitates timely acquisition of permits (all types)**	1	2	3	4	5
		DOES NOT — OCCASIONALLY — USUALLY — DOES		x	x	x	
	4.2	**Design is regulatory-, codes-, and standards-compliant**	1	2	3	4	5
		RARELY — OCCASIONALLY — USUALLY — COMPLETELY		x	x	x	
	4.3	**Design is adaptable to emerging standards, codes, and regulations**	1	2	3	4	5
		W/GREAT DIFFICULTY — W/SOME DIFFICULTY — EASILY		x	x	x	x
	4.4	**Design passes third-party certifications for compliance to specified codes and standards**	1	2	3	4	5
		DOES NOT — OCCASIONALLY — USUALLY — DOES		x	x		

Table H.5: Capital Cost Efficiency PVO Sub-Criteria

5	Capital Cost Efficiency					Timing				
5.1	Cost relative to peer projects					1	2	3	4	5
	BOTTOM QUARTILE	3RD QUARTILE	2ND QUARTILE	TOP QUARTILE				x	x	
5.2	Facility Total-Installed-Cost per unit									
5.2.1	5.2.1	Unit of production capacity				1	2	3	4	5
		VERY LOW	LOW	HIGH	VERY HIGH			x	x	
5.2.2	5.2.2	Unit of area				1	2	3	4	5
		VERY LOW	LOW	HIGH	VERY HIGH			x	x	
5.3	Design facilitates desired sourcing and supply strategies					1	2	3	4	5
	DOES NOT	OCCASIONALLY	USUALLY	DOES				x	x	
5.4	Efficient site selection and layout					1	2	3	4	5
	NOT AT ALL	SOMEWHAT	MOSTLY	VERY		x	x	x	x	x
5.5	"Biddable" design documents for the locale and market					1	2	3	4	5
	NONE	SOME	MANY	ALL			x	x		
5.6	Amount of design customization					1	2	3	4	5
	VERY HIGH	HIGH	LOW	VERY LOW		x	x	x		
5.7	Value Engineering savings are achieved					1	2	3	4	5
	VERY LOW	LOW	HIGH	VERY HIGH			x	x	x	
5.8	Design facilitates efficient construction and startup					1	2	3	4	5
	RARELY	OCCASIONALLY	USUALLY	COMPLETELY		x	x	x	x	
5.9	Design productivity					1	2	3	4	5
	VERY LOW	LOW	HIGH	VERY HIGH			x	x		

Table H.6: Operations & Maintenance Efficiency PVO Sub-Criteria

6	O&M Efficiency				Timing				
6.1	Energy efficiency relative to peer facilities				1	2	3	4	5
	BOTTOM QUARTILE	3RD QUARTILE	2ND QUARTILE	TOP QUARTILE		x	x	x	x
6.2	Design addresses and/or facilitates minimal facility life-cycle cost (total cost of ownership)				1	2	3	4	5
	DOES NOT	SOMEWHAT	MOSTLY	DOES		x	x	x	x
6.3	Design maximizes asset demand utilization (or facility availability factor)				1	2	3	4	5
	BOTTOM QUARTILE	3RD QUARTILE	2ND QUARTILE	TOP QUARTILE					x
6.4	Raw material yield efficiency relative to peer facilities				1	2	3	4	5
	BOTTOM QUARTILE	3RD QUARTILE	2ND QUARTILE	TOP QUARTILE				x	x
6.5	Annual unit cost of operations/maintenance/repair relative to peer facilities				1	2	3	4	5
	BOTTOM QUARTILE	3RD QUARTILE	2ND QUARTILE	TOP QUARTILE					x
6.6	Annual operator hours/units relative to peer facilities				1	2	3	4	5
	BOTTOM QUARTILE	3RD QUARTILE	2ND QUARTILE	TOP QUARTILE					x
6.7	Annual occupant/operator productivity relative to peer facilities				1	2	3	4	5
	BOTTOM QUARTILE	3RD QUARTILE	2ND QUARTILE	TOP QUARTILE					x
6.8	Waste disposal cost relative to peer facilities				1	2	3	4	5
	BOTTOM QUARTILE	3RD QUARTILE	2ND QUARTILE	TOP QUARTILE				x	x

Table H.7: Product / Plant / Service Quality PVO Sub-criteria

7		Product/Plant/Service Quality	Timing				
	7.1	**Manufactured product rejection rate**	1	2	3	4	5
		BOTTOM QUARTILE, 3RD QUARTILE, 2ND QUARTILE, TOP QUARTILE				x	x
	7.2	**Ability to accommodate variable feedstocks while maintaining consistent output**	1	2	3	4	5
		NO FEEDSTOCK VAR'N, SOME, UPPER PRACTICAL LIMIT					x
	7.3	**Plant reliability**	1	2	3	4	5
		BOTTOM QUARTILE, 3RD QUARTILE, 2ND QUARTILE, TOP QUARTILE					x
	7.4	**Fit-for-purpose/application; meets owner/end user requirements, including aesthetics, as appropriate**	1	2	3	4	5
		NO, SOMEWHAT, MOSTLY, YES	x	x	x	x	x
	7.5	**Satisfied customers at service facilities**	1	2	3	4	5
		NO, SOMEWHAT, MOSTLY, YES				x	x

Table H.8: Design and Construction Quality PVO Sub-criteria

8	Design & Construction Quality	Timing				
8.1	**Clarity of information/documents**	1	2	3	4	5
	NUMEROUS · SOME AREAS · VERY FEW · NO AREAS OF	x	x	x	x	
8.2	**Design coordinated within and across all technical disciplines**	1	2	3	4	5
	NEVER · OCCASIONALLY · USUALLY · ALWAYS	x	x	x	x	
8.3	**Design coordinated with key vendors and vendor design**	1	2	3	4	5
	NEVER · OCCASIONALLY · USUALLY · ALWAYS	x	x	x	x	
8.4	**Design work product checked and correct**	1	2	3	4	5
	NEVER · OCCASIONALLY · USUALLY · ALWAYS	x	x	x	x	
8.5	**Completeness of design documentation**	1	2	3	4	5
	NEVER · OCCASIONALLY · USUALLY · ALWAYS	x	x	x	x	
8.6	**Accuracy of drawings and data**	1	2	3	4	5
	VERY LOW · LOW · HIGH · VERY HIGH	x	x	x	x	
8.7	**Timeliness of Designer RFI (or Field Change Request) response**	1	2	3	4	5
	VERY POOR · POOR · GOOD · OUTSTANDING		x	x		
8.8	**Frequency of non-Owner-directed design change**	1	2	3	4	5
	ALL · MANY · FEW · NONE		x	x	x	
8.9	**Frequency of RFIs (or Field Change Requests) driven by conflicting or missing design information**	1	2	3	4	5
	ALL · MANY · FEW · NONE		x	x	x	
8.10	**Error-driven design rework: design rework hours/design hour budget**	1	2	3	4	5
	VERY HIGH · HIGH · LOW · VERY LOW	x	x	x	x	
8.11	**Error-driven design rework: design time delay/planned design duration**	1	2	3	4	5
	VERY HIGH · HIGH · LOW · VERY LOW	x	x	x	x	
8.12	**Frequency of Design error/omission-driven change orders (or field rework)**	1	2	3	4	5
	VERY MANY · MANY · FEW · NONE			x	x	x
8.13	**Design addresses and/or facilitates Constructability**	1	2	3	4	5
	IS NOT · MODERATE · AVERAGE · VERY GOOD · EXCELLENT	x	x	x	x	
8.14	**Design addresses and/or facilitates procurability (i.e., via component availability)**	1	2	3	4	5
	IMPOSSIBLE · DIFFICULT · NORMAL · EASY	x	x	x		
8.15	**Configuration management and/or approvals management**	1	2	3	4	5
	OUT OF COMPLIANCE · IN COMPLIANCE			x	x	
8.16	**Document revision control**	1	2	3	4	5
	NONE · LATE OR INACCURATE · MOST · TIMELY & ACCURATE	x	x	x	x	
8.17	**Packaging of construction contracts and sub-contracts**	1	2	3	4	5
	VERY POOR · POOR · GOOD · GREAT		x	x	x	
8.18	**Design effectiveness in elimnating physical interferences**	1	2	3	4	5
	NONE · OCCASIONALLY · USUALLY · ALWAYS		x	x	x	
8.19	**Appropriate level of design detail for project location**	1	2	3	4	5
	IS NOT · SOMEWHAT · GOOD · EXCELLENT		x	x	x	
8.20	**Use of materials, components, and methods appropriate for location**	1	2	3	4	5
	NEVER · OCCASIONALLY · USUALLY · ALWAYS	x	x	x	x	
8.21	**Verification of as-builts of existing facility at start of design**	1	2	3	4	5
	NEVER · OCCASIONALLY · USUALLY · ALWAYS	x	x	x	x	
8.22	**Design model data accessible/usable by fabricator, constructors**	1	2	3	4	5
	DOES NOT · SOMEWHAT · GOOD · EXCELLENT		x	x	x	x

Table H.9: Schedule Reduction PVO Sub-criteria

9	Schedule Reduction	Timing				
9.1	**Timely review of submittals and RFIs**	1	2	3	4	5
	NEVER — OCCASIONALLY — USUALLY — ALWAYS	x	x	x	x	
9.2	**Amplifying design resources with appropriate outsourcing (exploiting efficiency of specialists)**	1	2	3	4	5
	NEVER — OCCASIONALLY — USUALLY — ALWAYS	x	x	x		
9.3	**How effective is design in reducing overall project duration (compared to similar projects)**	1	2	3	4	5
	VERY INEFFECTIVE — INEFFECTIVE — EFFECTIVE — VERY EFFECTIVE			x	x	
9.4	**Adequate/efficient level of site investigation**	1	2	3	4	5
	VERY LOW — LOW — HIGH — VERY HIGH	x	x	x	x	
9.5	**Leveraging CAD model with fabrication**	1	2	3	4	5
	NEVER — OCCASIONALLY — USUALLY — ALWAYS		x	x	x	
9.6	**Design schedule milestone compliance**	1	2	3	4	5
	NEVER — OCCASIONALLY — USUALLY — ALWAYS	x	x	x		
9.7	**Duration of design for long-lead items accelerates project schedule**	1	2	3	4	5
	SIGNIFICANTLY DELAYS — DELAYS — ACCELERATES — GREATLY ACCELERATES	x	x	x	x	
9.8	**Design meets schedule demands from construction season shutdowns/requirements**	1	2	3	4	5
	NEVER — OCCASIONALLY — USUALLY — ALWAYS	x	x	x	x	
9.9	**Use of schedule-efficient components, materials and methods**	1	2	3	4	5
	NEVER — OCCASIONALLY — USUALLY — ALWAYS		x	x	x	
9.10	**Degree of repetition/modularity**	1	2	3	4	5
	VERY LOW — LOW — HIGH — VERY HIGH		x	x		
9.11	**Schedule reduction from 3-D CAD, CAE, etc. (design and construction)**	1	2	3	4	5
	VERY LOW — LOW — HIGH — VERY HIGH		x	x	x	
9.12	**Time savings from Value Engineering**	1	2	3	4	5
	VERY LOW — LOW — HIGH — VERY HIGH				x	

Table H.10: Environmental Stewardship PVO Sub-criteria

10	Environmental Stewardship					Timing				
10.1	Design minimizes emissions, byproducts, and/or waste production (e.g., air, water, solids, etc.)					1	2	3	4	5
	DOES NOT MEET GOALS		MEETS GOALS		EXCEEDS GOALS	x	x	x	x	x
10.2	Design minimizes consumption of resources (water, electricity, fuel, etc.)					1	2	3	4	5
	DOES NOT	SOMEWHAT		MOSTLY	DOES	x	x	x	x	x
10.3	Design minimizes physical footprint on the site					1	2	3	4	5
	DOES NOT	SOMEWHAT		MOSTLY	DOES			x		
10.4	Design maximizes use of recycled/renewable materials					1	2	3	4	5
	DOES NOT	SOMEWHAT		MOSTLY	DOES		x	x	x	
10.5	Design enhances indoor environment for facility occupants					1	2	3	4	5
	DOES NOT	SOMEWHAT		MOSTLY	DOES		x	x	x	x
10.6	Design minimizes and/or offsets impacts to nature with respect to site location, wetlands, creation/use of open space, habitat, etc.					1	2	3	4	5
	DOES NOT	SOMEWHAT		MOSTLY	DOES	x	x			
10.7	Design improves local environment (e.g., increase of green space, water availability and quality, provision of parkland/outdoor facilities)					1	2	3	4	5
	DOES NOT	SOMEWHAT		MOSTLY	DOES	x	x			
10.8	Design fosters recycling of building materials and equipment after use					1	2	3	4	5
	DOES NOT	SOMEWHAT		MOSTLY	DOES		x	x		
10.9	Design adheres to voluntary environmental standards, such as LEED, ISO 14000(?)					1	2	3	4	5
	DOES NOT MEET STANDARDS		MEETS STANDARDS		EXCEEDS STANDARDS	x	x	x		
10.10	Design includes life-cycle assessment to lower total environmental impact of facility					1	2	3	4	5
	NONE		BASIC		DETAILED	x	x			

Table H.11: Flexibility for Future Use PVO Sub-criteria

11	Flexibility for Future Use					Timing				
11.1	Structure(s) designed to be adaptable for different process or use (e.g., layout can be reconfigured, expansion such as new levels/floors and size)					1	2	3	4	5
	IS NOT	SOMEWHAT		MOSTLY	FULLY		x	x	x	x
11.2	Design facilitates conversion to different fuel or feedstock					1	2	3	4	5
	DOES NOT	SOMEWHAT		MOSTLY	FULLY		x	x	x	x
11.3	Design contains capability to expand, add capacity, or contract (i.e., scalability)					1	2	3	4	5
	DOES NOT	SOMEWHAT		MOSTLY	FULLY		x	x	x	x
11.4	Design facilitates future use of or increase in automation level (e.g., equipment, material handling, etc.)					1	2	3	4	5
	DOES NOT	SOMEWHAT		MOSTLY	FULLY		x	x	x	x
11.5	Design includes components that facilitate removal, reuse, and/or recycling					1	2	3	4	5
	DOES NOT	SOMEWHAT		MOSTLY	FULLY		x	x	x	x
11.6	Facility is designed for ease of decommissioning, dismantling, and closure					1	2	3	4	5
	IS NOT	SOMEWHAT		MOSTLY	FULLY		x	x	x	x
11.7	Design supports expansion for increased/different staffing levels (e.g., future conversion to office blocks, services for cafeterias, etc.)					1	2	3	4	5
	DOES NOT	SOMEWHAT		MOSTLY	FULLY		x	x	x	x

Appendix I:
Design Effectiveness Evaluation Tool User Manual

Before Starting:

- Select "Enable Macros" when prompted at the start of the program.
- To Save and Exit during the sub-criteria selection, use the buttons provided at the bottom of the tool. Saving with the default Excel ™ function <CTRL+S> on the Sub-criteria pages might cause them to function improperly upon restarting the program.

Evaluation Tool Introduction:

This tool is intended to assist in the evaluation of design effectiveness (DE) for capital projects (as opposed to selection of DEPs). The tool provides guidance in assessing how well a project is meeting desired objectives and criteria for design effectiveness.
The tool calculates a DE performance score based on the following factors:

- Timing of the evaluation;
- Relative importance of 11 different Project Value Objectives (PVOs);
- Selected or screened sub-criteria;
- Assessments of individual sub-criteria; and
- Significance weightings of evaluation sub-criteria associated with targeted PVOs.

Please be aware of interdependency among sub-criteria during evaluation. A table has been provided in the tool (access the button on the bottom of the sub-criteria evaluation pages) in order to help the user identify potential overlapping sub-criteria.

Evaluation Tool Sheet Progression:

The selection tool follows a logical progression of pages or screens for data entry. The screens are listed immediately below, and explained in the following sections of this appendix.

1. Introduction
2. Project Information
3. Timing of Evaluation
4. Relative Significance of Project Value Objectives
    a. Editing Sub-criteria weights
5. Sub-criteria Selection and Evaluation
6. Results
    a. Review Sub-criteria Weights

Page by Page Walkthrough:

Introduction:
This page presents the selection tool's purpose and limitations. Click on the "Continue" button to proceed.

Project Information:
This page asks the user to input basic information about the project for which design effectiveness is being implemented. None of the fields are required to proceed, although filling out the fields for record keeping is recommended. Click the "Continue" button to proceed.

Timing of Evaluation:
This page asks the user to indicate the approximate timing of the evaluation. Note that the evaluation timing affects the suitability of some sub-criteria. Click the "Continue" button to proceed.

Relative Significance of Project Value Objectives:
This page asks the user to indicate the relative significance of the Project Value Objectives. The user may indicate the relative significance with "N/A", "Low", "Med", "High", or "Custom". The "weight factor" is "0", "1", "2", "3", and "custom", respectively. Selecting a "Custom" level of significance allows the user to input his/her own Weight Factors for that PVO.

The user may also customize the sub-criteria weights for each of the Project Value Objectives by clicking on the "customize" button under the "Edit Sub-Criteria Weights" box. The user may revert back to the default sub-criteria weights (the PVO's sub-criteria weighted equally) by clicking the "Default" button next to the "customize" button. An indicator next to these two buttons will remind the user of the status of the sub-criteria weights.

Clicking the "Accept & Continue" button will also update the lists, and will send the user to the next step in the evaluation process.

Edit Sub-Criteria Weights:
By clicking the "Customize Sub-Criteria Weights" button for a given PVO, the user is taken to a different page where each of the sub-criteria weights can be adjusted. The user may edit a PVO's sub-criteria weights by inputting a weight factor for the sub-criteria. The default setting is a weight factor of "1" for all sub-criteria, thus making all the sub-criteria of a given PVO equally weighted by

default. Editing the sub-criteria weights gives the user the add flexibility option of allowing some sub-criteria to be more significant than others, allowing the evaluation score given for heavier-weighted sub-criteria to have a greater influence on the overall evaluation score. Editing sub-criteria weights is an optional process.

Sub-Criteria Selection and Evaluation:

The user is asked to evaluate or score the sub-criteria for each of the PVO's selected previously. Evaluation uses a 0-10 scale, with the option of excluding sub-criteria that do not apply. Each sub-criterion has a descriptive scale that helps the user in the evaluation process (e.g.: 0 = Never, 3 = Seldom, 7 = Regularly, 10 = Always). Scales vary for each criterion. Please take note that some sub-criteria may be interdependent.

The user is highly advised to use the Sub-Criteria Interdependence table link provided at the bottom of the page.

Results:

This page presents the score of each PVO, and the composite score based on the weighted score of all the PVO's. The user may review and modify the sub-criteria weights by clicking on the "Review Sub-Criteria Weights" button. A "Score Interpretation" button is provided near the composite score to give the user more insight into score values.

Review Sub-Criteria Weights:

Similar to the "Edit Sub-Criteria Weights" function on the "Relative Significance of PVOs" page. The user may review and edit all the 11 PVOs' sub-criteria weights. Results will be recalculated based on the new weights.

Design Effectiveness Evaluation Tool Algorithm

This section provides and overview of the calculations and steps supporting evaluation.

1. User selects timing of evaluation to qualify/disqualify sub-criteria for evaluation.
    - For each sub-criterion, "T", the timing influence, is obtained from the Sub-Criteria Timing Matrix.
    - "T" can be a value of 1 or 0, indicating whether the sub-criteria is appropriate for the selected timing of evaluation or not. This affects which sub-criteria are designated as "Not Applicable" at the start of their evaluation. If all of a PVO's sub-criteria are not applicable due to timing, then the PVO will be designated as N/A at the start of the PVO weighting section.

2. User assigns weights for the Project Value Objectives and sub-criteria.
    - A level multiplier is determined for each PVO according to the selected level: N/A = 0, Low = 1, Med = 2, High = 3.
    - The weight percentages are determined by dividing the PVO's weight factor over the sum of all weight factors (selecting all PVOs as Low will give the same weight percentage as selecting them all as Medium).
    - The sub-criteria weight percentages can also be customized and are derived by dividing a sub-criteria's weight factor over the sum of *applicable* PVO's sub-criteria's weight factors. By default, all of a PVO's sub-criteria are weighted equally.

3. User Evaluates Sub-criteria
    - User scores each sub-criteria on a scale of 0-10.
    - N/A PVO's criteria will not be scored.

4. The Composite Score is calculated as follows:
    - Each PVO's score is derived from the sum-product of the PVO's sub-criteria and their weights (which is adjusted to exclude non-applicable selections). The composite score is the sum product of the PVO scores and their weights. The composite score ranges from 0-10.

Troubleshooting:

Cannot Proceed Beyond Introduction Page:

Problem: Clicking the "Continue" button on the introduction page does nothing.
Solution: Make sure to "Enable Macros" when prompted at the start of the file launch. Otherwise, make sure your macro security settings are on "medium" by selecting tools → options → security (tab) → macro settings.

Disappearing or Inappropriately-Sized Buttons:

Problem: Buttons are not being displayed, or they are being displayed in an inappropriate size that is causing overlapping buttons to be displayed.
Solution: Set your screen resolution to 1024x768. Also make sure your program window is on full-screen view. Note that some old-model projectors are also known to have problems displaying buttons.

No "Sub-Criteria Selection" and "Results" Page Buttons:

Problem: No buttons displayed on the "Sub-Criteria Selection" and "Results" page.
Solution: Scroll to the bottom of the page using the scroll bar or the mouse wheel.

Results Have Several “N/A” Values:
Problem: The Results page has “N/A” values.
Solution: Some of the PVO’s might be inappropriate for the selected timing of the evaluation. PVOs with all sub-criteria selected as “does not apply” will also be categorized as “N/A”

Small Text:
Problem: The text is too small to read.
Solution: Set your screen resolution to 1024x768. You can also increase the window zoom by selecting View → Zoom from your toolbar

Buttons Do Not Activate:
Problem: Clicking buttons does nothing.
Solution: Click on a cell away from the button and try again. If that does not work, there is the rare possibility that you are in Control Toolbox Design Form. Click on View → Toolbars → Control Toolbox and toggle the Design Mode icon on and off. If buttons can be dragged and dropped, then you are in Design Mode and the buttons are not active. Once you toggle Design Mode off, turn off the Control Toolbox and proceed with the program.

Appendix J: Evaluation Sub-Criteria Interdependence

Scale:
1 = Very Low Interdependency
10 = Very High Interdependency

Sub-Criteria Interdependence Matrix

Criterion	No.	Sub-criterion	1.5 IP and design information are handled in a manner consistent with security requirements	2.2 Design incorporates industry/corporation safety standards, best practices, and lessons-learned	3.2 Design is compliant with applicable construction safety codes and regulations	4.2 Design is regulatory-, codes-, and standards-compliant	4.3 Design is adaptable to emerging standards, codes, and regulations	4.4 Design passes third-party certifications for compliance to specified codes and standards	5.8 Design facilitates efficient construction and startup	7.3 Plant reliability	8.6 Accuracy of drawings and data	8.9 Frequency of RFIs (or Field Change Requests) driven by conflicting or missing design information	8.14 Design addresses and/or facilitates procurability	8.16 Document revision control
1 Security	1.1	Facility detects and responds to physical breaches as required	1	1	1	1	1	1	1	1	1	1	1	1
	1.2	Security of facility information systems is addressed	**7**	1	1	1	1	1	1	1	1	1	1	1
2 O&M Safety	2.1	Design is compliant with O/M safety regulations and codes, as required		**7**	**7**	**8**	**7**	1	1	1	1	1	1	1
	2.2	Design incorporates industry/corporation safety standards, best practices, and lessons-learned		x	**7**	**8**	**7**	1	1	1	1	1	1	1
	2.3	Design incorporates HAZOP, PHA, and PSM input			1	1	4	**8**	1	1	1	1	1	1
	2.4	Design Incorporates O/M accessibility and ergonomics			1	1	1	1	1	1	1	1	1	1
	2.5	Design supports safe startup/operations/shut-down/decommissioning at all levels (i.e., plant, systems, etc.)			1	1	1	1	**7**	1	1	1	1	1
3 Construction Safety	3.1.1	Falls protection			1	1	1	1	1	1	1	1	1	1
	3.2	Design is compliant with applicable construction safety codes and regulations			x	**8**	1	1	1	1	1	1	1	1
4 Regulatory & Standards Compliance	4.1	Design documentation facilitates timely acquisition of permits (all types)				1	1	1	1	1	1	1	1	1
	4.2	Design is regulatory-, codes-, and standards-compliant				x	**7**	1	1	1	1	1	1	1
	4.4	Design passes third-party certifications for compliance to specified codes and standards						x	1	1	1	1	1	1
5 Capital Cost Efficiency	5.1	Cost relative to peer projects							1	1	1	1	1	1
5.2 Facility Total-	5.2.1	Unit of production capacity							1	1	1	1	1	1
	5.4	Efficient site selection and layout							1	1	1	1	1	1

Scale:
1 = Very Low Interdependency
10 = Very High Interdependency

Sub-Criteria Interdependence Matrix

			Use of materials, components, and methods appropriate for location	Timely review of submittals and RFIs	Use of schedule-efficient components, materials and methods	Degree of repetition/modularity	Design minimizes emissions, byproducts, and/or waste production (e.g., air, water, solids, etc.)	Design minimizes consumption of resources (water, electricity, fuel, etc.)	Design minimizes physical footprint on the site	Design minimizes and/or offsets impacts to nature with respect to site location, wetlands,	Design adheres to voluntary environmental standards, such as LEED, ISO 14000(?)	Structure(s) designed to be adaptable for different process or use (e.g., layout can be reconfigured, expansion such as new	Design facilitates conversion to different fuels or feedstock	Design contains capability to expand, add capacity, or contract (i.e., scalability)
			8.20	9.1	9.9	9.10	10.1	10.2	10.3	10.6	10.9	11.1	11.2	11.3
1 Security	1.1	Facility detects and responds to physical breaches as required	1	1	1	1	1	1	1	1	1	1	1	1
	1.2	Security of facility information systems is addressed	1	1	1	1	1	1	1	1	1	1	1	1
2 O&M Safety	2.1	Design is compliant with O/M safety regulations and codes, as required	1	1	1	1	1	1	1	1	1	1	1	1
	2.2	Design incorporates industry/corporation safety standards, best practices, and lessons-learned	1	1	1	1	1	1	1	1	**7**	1	1	1
	2.3	Design incorporates HAZOP, PHA, and PSM input	1	1	1	1	1	1	1	1	1	1	1	1
	2.4	Design Incorporates O/M accessibility and ergonomics	1	1	1	1	1	1	1	1	1	1	1	1
	2.5	Design supports safe startup/operations/shut-down/decommissioning at all levels (i.e., plant, systems, etc.)	1	1	1	1	1	1	1	1	1	1	1	1
3 Construction Safety	3.1.1	Falls protection	1	1	1	1	1	1	1	1	1	1	1	1
	3.2	Design is compliant with applicable construction safety codes and regulations	1	1	1	1	1	1	1	1	1	1	1	1
4 Regulatory & Standards Compliance	4.1	Design documentation facilitates timely acquisition of permits (all types)	1	1	1	1	1	1	1	1	1	1	1	1
	4.2	Design is regulatory-, codes-, and standards-compliant	1	1	1	1	1	1	1	1	1	1	1	1
	4.4	Design passes third-party certifications for compliance to specified codes and standards	1	1	1	1	1	1	1	1	**7**	1	1	1
5 Capital Cost Efficiency	5.1	Cost relative to peer projects	1	1	1	1	1	1	1	1	1	1	1	1
5.2 Facility Total-	5.2.1	Unit of production capacity	1	1	1	1	1	1	1	1	1	1	1	1
	5.4	Efficient site selection and layout	1	1	1	1	1	1	**7**	**7**	1	**8**	1	1

Scale:
1 = Very Low Interdependency
10 = Very High Interdependency

Sub-Criteria Interdependence Matrix

			IP and design information are handled in a manner consistent with security requirements	Design incorporates industry/corporation safety standards, best practices, and lessons-learned	Design is compliant with applicable construction safety codes and regulations	Design is regulatory-, codes-, and standards-compliant	Design is adaptable to emerging standards, codes, and regulations	Design passes third-party certifications for compliance to specified codes and standards	Design facilitates efficient construction and startup	Plant reliability	Accuracy of drawings and data	Frequency of RFIs (or Field Change Requests) driven by conflicting or missing design information	Design addresses and/or facilitates procurability	Document revision control
			1.5	2.2	3.2	4.2	4.3	4.4	5.8	7.3	8.6	8.9	8.14	8.16
6 O&M Efficiency	6.1	Higher efficiency of energy consumption relative to peer facilities								1	1	1	1	1
	6.8	Waste disposal cost relative to peer facilities								1	1	1	1	1
7 Product/ Plant/ Service Quality	7.1	Manufactured product rejection rate								**7**	1	1	1	1
	7.2	Ability to accommodate variable feedstocks while maintaining consistent output								1	1	1	1	1
8 Design & Construction Quality	8.1	Clarity of information/documents									1	**7**	1	1
	8.2	Design coordinated within and across all technical disciplines									1	1	1	1
8.1 Design Quality	8.3	Design coordinated with key vendors and vendor design									1	1	**8**	1
	8.4	Design work product checked and correct									**7**	5	1	**7**
	8.5	Completeness of design documentation									1	**7**	1	1
	8.6	Accuracy of drawings and data									x	1	1	5
	8.7	Timeliness of Designer RFI (or Field Change Request) response										1	1	1
	8.13	Design addresses and/or facilitates Constructability											1	1
8.2 Construction Quality	8.16	Document revision control												x
	8.20	Use of materials, components, and methods appropriate for location												
	9.9	Use of schedule-efficient components, materials and methods												
	9.10	Degree of repetition/modularity												
11 Flexibility for Future Use	11.1	Structure(s) designed to be adaptable for different process or use (e.g., layout can be reconfigured, expansion such as new levels/floors and size)												

Scale:
1 = Very Low Interdependency
10 = Very High Interdependency

Sub-Criteria Interdependence Matrix

Criteria	No.	Sub-Criteria	8.20 Use of materials, components, and methods appropriate for location	9.1 Timely review of submittals and RFIs	9.9 Use of schedule-efficient components, materials and methods	9.10 Degree of repetition/modularity	10.1 Design minimizes emissions, byproducts, and/or waste production (e.g., air, water, solids, etc.)	10.2 Design minimizes consumption of resources (water, electricity, fuel, etc.)	10.3 Design minimizes physical footprint on the site	10.6 Design minimizes and/or offsets impacts to nature with respect to site location, wetlands,	10.9 Design adheres to voluntary environmental standards, such as LEED, ISO 14000(?)	11.1 Structure(s) designed to be adaptable for different process or use (e.g., layout can be reconfigured, expansion such as new	11.2 Design facilitates conversion to different fuels or feedstock	11.3 Design contains capability to expand, add capacity, or contract (i.e., scalability)
6 O&M Efficiency	6.1	Higher efficiency of energy consumption relative to peer facilities	1	1	1	1	1	**7**	1	1	1	1	1	1
	6.8	Waste disposal cost relative to peer facilities	1	1	1	1	**7**	1	1	1	1	1	1	1
7 Product/ Plant/ Service Quality	7.1	Manufactured product rejection rate	1	1	1	1	1	1	1	1	1	1	1	1
	7.2	Ability to accommodate variable feedstocks while maintaining consistent output	1	1	1	1	1	1	1	1	1	1	**7**	1
8 Design & Construction Quality	8.1	Clarity of information/documents	1	1	1	1	1	1	1	1	1	1	1	1
	8.2	Design coordinated within and across all technical disciplines	1	1	1	1	1	1	1	1	1	1	1	1
8.1 Design Quality	8.3	Design coordinated with key vendors and vendor design	1	1	1	1	1	1	1	1	1	1	1	1
	8.4	Design work product checked and correct	1	1	1	1	1	1	1	1	1	1	1	1
	8.5	Completeness of design documentation	1	1	1	1	1	1	1	1	1	1	1	1
	8.6	Accuracy of drawings and data	1	1	1	1	1	1	1	1	1	1	1	1
	8.7	Timeliness of Designer RFI (or Field Change Request) response	1	**9**	1	1	1	1	1	1	1	1	1	1
	8.13	Design addresses and/or facilitates Constructability	1	1	**7**	1	1	1	1	1	1	1	1	1
8.2 Construction Quality	8.16	Document revision control	**7**	1	1	1	1	1	1	1	1	1	1	1
	8.20	Use of materials, components, and methods appropriate for location	x	1	1	1	1	1	1	**7**	1	1	1	1
	9.9	Use of schedule-efficient components, materials and methods			x	**7**	1	1	1	1	1	1	1	1
	9.10	Degree of repetition/modularity				x	1	1	1	1	1	1	1	1
11 Flexibility for Future Use	11.1	Structure(s) designed to be adaptable for different process or use (e.g., layout can be reconfigured, expansion such as new levels/floors and size)										x	4	**7**

Appendix K: RT 233 Members

William R. Boyd, Southern Company

Kent Cori, CH2M Hill

Maria E. DeIsasi, Smithsonian Institution

Adalberto Franco, Petrobras

Carlos A. Igreja, Petrobras

Donald Lindstrom, Abbott

William J. O'Brien, University of Texas at Austin

James T. O'Connor, University of Texas at Austin

John E. Pinho, Intel Corporation

Mark Reuss, Bechtel National, Inc.

Larry Rogers, U.S. Army Corps of Engineers

Scott R. Sargent, Victaulic Company

Sam A. Scucci, The Shaw Group Inc.

Travis E. Twardowski, Rohm and Haas Company

Summary of Member Experience:

1. Number of Members: 14
2. Average years of industry experience: 22.7
3. Total years of industry experience: 318
4. Total years of Design Engineering Experience: 70 (8.8 years average)
5. Total years of Design Management Experience: 53 (7.6 years average)
6. Total years of Construction Management Experience: 33 (6.6 years average)
7. Total years of Project Management Experience: 63 (7.0 years average)
8. Total years Other Experience: 104 (11.6 years average)
9. Average Number of different roles / titles: 2.9
10. Number of members with Commercial / Building Experience: 2
11. Number of Members with Industrial Experience: 11
12. Number of Members with Heavy / Civil / Infrastructure Experience: 3
13. Number of Members with Housing Experience: 1
14. Number of Members with Structural Background: 2
15. Number of Members with Site / Civil Background: 2
16. Number of Members with Mechanical Background: 2
17. Number of Members with Electrical Background: 2
18. Number of Members with Architectural Background: 2
19. Number of Members with Other Background: 4
20. Number of Members with average project size <$15M: 2
21. Number of Members with average project size $15M - $50M: 6
22. Number of Members with average project size >$50M: 6

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Vita

Ra'ed Tahseen Jarrah was born in Jeddah, Saudi Arabia on August 9, 1982. The son of Tahseen Fawzi Jarrah and Hiba M. Hassan Saadi. After completing his studies at Rawdah High School in Beirut, Lebanon, in 2000, he attended the American University of Beirut and graduated with a degree of Bachelor of Engineering in Civil Engineering in July 2004. In August 2004, he entered the Construction Engineering and Project Management graduate program at the University of Texas at Austin, and graduated with a Masters Degree in Civil Engineering in August 2005.

Permanent Address: 2108 Redondo Dr. McKinney, TX 75071

This dissertation was typed by the author